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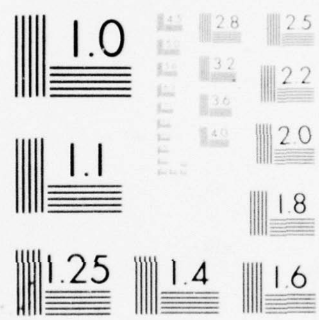

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NETWORK TIMING/SYNCHRONIZATION EVALUATION MODELING

Clarkson College of Technology

ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

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Digital transmission techniques are expected to play an important role in future Defense Communication Systems, since they offer many advantages over analog methods. One of the important requirements for digital transmission is synchronization of nodal clocks. This report evaluates four proposed synchronization techniques (Discrete-Control-Correction, Master Slave, Independent Clocks, and Time Reference Distribution) with respect to a set of overall system objectives. It is found that of the proposed techniques,

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the time reference distribution technique with further refinements will best meet the DCS requirements.

PREFACE

This effort was conducted by Clarkson College of Technology under the sponsorship of the Rome Air Development Center Post-Doctoral Program for Defense Communications Agency (DCA). Harris Stover of DCA was the task project engineer and provided overall technical direction and guidance.

The RADC Post-Doctoral Program is a cooperative venture between RADC and some sixty-five universities eligible to participate in the program. Syracuse University (Department of Electrical and Computer Engineering), Purdue University (School of Electrical Engineering), Georgia Institute of Technology (School of Electrical Engineering), and State University of New York at Buffalo (Department of Electrical Engineering) act as prime contractor schools with other schools participating via sub-contracts with the prime schools. The U.S. Air Force Academy (Department of Electrical Engineering), Air Force Institute of Technology (Department of Electrical Engineering), and the Naval Post Graduate School (Department of Electrical Engineering) also participate in the program.

The Post-Doctoral Program provides an opportunity for faculty at participating universities to spend up to one year full time on exploratory development and problem-solving efforts with the post-doctorals splitting their time between the customer location and their educational institutions. The program is totally customer-funded with current projects being undertaken for Rome Air Development Center (RADC), Space and Missile Systems Organization (SAMSO), Aeronautical Systems Division (ASD), Electronic Systems Division (ESD), Air Force Avionics Laboratory (AFAL), Foreign Technology Division (FTD), Air Force Weapons Laboratory (AFWL), Armament Development and Test Center (ADTC), Air Force Communications Service (AFCS), Aerospace Defense Command

(ADC), Hq USAF, Defense Communications Agency (DCA), Navy, Army, Aerospace Medical Division (AMD), and Federal Aviation Administration (FAA).

Further information about the RADC Post-Doctoral Program can be obtained from Jacob Scherer, RADC/RBC, Griffiss AFB, NY, 13441, telephone AV 587-2543, COMM (315) 330-2543.

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CHAPTER 1.

INTRODUCTION

Network timing and synchronization are becoming ever more important in the field of communications. In particular, the switching and multiplexing of digital communications channels depends heavily on the ability of a network to maintain synchronization. For example, time division switching requires that the switch and the incoming channels have a common time reference. Even where time division switching is not used, such as, for example, in a space division switch, various digital data streams must be multiplexed together to form data streams which effectively utilize the available bandwidth of the communications links. The processes of switching and multiplexing are used to create networks. Networking is currently the only cost effective means for providing digital or even analog communications on a large scale [1,2,3,4,5].

Digital transmission techniques have many advantages over analog transmission. The error rate in digital systems is extremely low compared to analog systems and can be improved considerably by coding and error recovery methods. Furthermore, digital techniques provide for the ready implementation of cryptographic and other security techniques such as digitized secure voice.

The advantages of digital transmission techniques have justified the conversion of large scale communications networks from analog to digital mode of operation. Of course, one cannot simply change instantaneously from one system to another. This places considerable restrictions on the synchronization technique used since the digital and analog parts of the network must interoperate during the many transition phases from an analog to a totally digital network.

In designing a digital communications system, a definite set of fundamental performance goals or objectives must be established. Performance criteria for various alternative approaches can then be evaluated in light of such fundamental requirements. For the future Defense Communications System, the following four requirements appear to be the most crucial to a successful system design:

1. To endure, i.e., to maintain acceptable operation even in the event of perturbations such as partial physical destruction, component failures, enemy spoofing and/or jamming,
2. To interoperate, i.e., to communicate with other networks which may be using different operating techniques,
3. To be monitorable, i.e., to permit convenient acquisition of information pertinent to the evaluation, control, protection, maintenance, repair and modification of the system,
4. To be economical, i.e., to maximize the capabilities of 1, 2 and 3 above while minimizing the total procurement, operation, maintenance repair and modification costs.

In this report, four synchronization techniques (Discrete-Control Correction, Master Slave, Independent Clocks, and Time Reference Distribution) are evaluated with respect to this set of overall system objectives. In fact, this set of system objectives or goals are indeed very general and could be applied to almost any system with only slight changes in the wording.

Hence, the optimal communications system should endure, interoperate, be monitorable, and be economical.

This report presents the results of an initial investigation into the advantages and disadvantages of existing timing and synchronization techniques

as they apply to digital communication networks. Basically, four fundamental techniques were considered. These are: master-slave, discrete-control-correction, independent clocks, and time dissemination. The master-slave technique uses a fixed or selectable network structure to propagate timing information. Discrete-control-correction is a discrete time analog of frequency averaging wherein each node tracks a weighted average of the frequencies arriving over its communications links. Independent clocks is the mode of operation wherein each node of the network uses its own independent but precise clock. Finally, time dissemination, or more properly, precise time and time interval (PTTI) dissemination, is a technique which passes time throughout a network by starting at some master node and removing the time delays down through a hierarchical structure to provide Precise Time and Time Interval at the subordinate nodes. To be effective, this method should automatically select the best clock in the network as the master and also select the best path for transmission of the timing information. These four techniques are described in more detail in Chapter 2.

The technique of pulse stuffing was not considered in this work since it was felt that this method was more appropriate for link synchronization rather than to the performance of the overall network. This opinion, from a network viewpoint, is not likely to change due to the large communications overhead which is necessary to maintain network synchronization when several levels of multiplexing and switching are considered.

Since these techniques represent widely different modes of operation, it is essential to select criteria for comparing their performance which can be applied to each of these methods. Chapter 3 presents the criteria selected for this study. A description of each criterion and the justification for

its selection are also presented. These criteria are then used in the comparative study of Chapter 4. The comparison itself is based more on qualitative rather than quantitative information. Since the systems are so different, it is almost impossible for many of these criteria to be compared quantitatively. However, it is felt that the qualitative comparison is sufficient to justify the selection of an appropriate direction to be followed in defining the best synchronization techniques for future digital communications systems.

The terminology used in Chapters 3 and 4 to compare the performance of the different techniques was very carefully defined in an effort to prevent any misunderstanding or misinterpretation of the results presented. Therefore, one should be very careful in reading this material since careless interpretation of the phrases (which might have different meanings in the trade jargon) could indeed considerably change the interpretation and implications of these results.

A considerable amount of effort in this study was spent on bringing each of the techniques up to the level where they could be equitably compared. This is particularly true for the time dissemination technique. In order for this technique to be as effective as possible, the master node and the path of time dissemination should be automatically selected on a dynamic basis. Although existing techniques would provide this type of selection when starting from a fixed set of initial conditions, these techniques would not select the appropriate parameters when certain perturbations occur in the given network. Previous rules for path and master node selection were modified to form a new set of rules which can be used to dynamically select the appropriate network time dissemination structure under <u>all</u> operating conditions. This new set of rules is presented in Chapter 5. A proof that these rules will always select the

appropriate structure is given in Chapter 6. This particular set of rules may not be the best from an operational viewpoint; however, it does positively establish the existence of a technique for selecting the best route for disseminating precise time.

In order to evaluate the performance of different rules for disseminating precise time, a set of random test networks was generated. A description of this set of networks and the computer program which generated them is presented in Chapter 7. Furthermore, Chapter 8 describes the simulation results of these test networks for the technique described in Chapter 5 as well as for some alternative rules which were considered.

Chapter 9 is a preliminary description of a general test network which could eventually be used to evaluate the different synchronization techniques. This network represents an attempt to include network substructures which typically cause synchronization problems. Furthermore, it tries to represent the distribution of nodal clocks and communications links found in a realistic network.

Finally, the direction this work has provided is interpreted in Chapter 10. Also included in this chapter are recommendations for future work which should be pursued in determining the character and structure of the synchronization technique best suited to future digital communications networks.

CHAPTER 2.

DESCRIPTION OF SYNCHRONIZATION TECHNIQUES UNDER CONSIDERATION

This chapter gives a brief description of the different techniques of synchronization that are being considered.

1. Master-Slave Method [11,12]

In this method, all the nodes of the network are 'slaved' in their timing to the reference timing from a designated master node. Each node receives the reference timing either on a direct link from the master node or over a predetermined chain of links along which the reference timing is re-transmitted by the intermediate nodes. Thus, there is a hierarchy of nodes descending from the master node. Each node slaves itself to a fixed neighbor higher in the hierarchy and thus all the nodes are, in effect, slaved to the master node. A node slaves itself to the reference timing as received without attempting to correct for the time of propagation from the sending node.

In case a node loses its reference timing due to failure of a link, provision can be made for the node to switch to a pre-assigned alternative link or to operate as an independent clock until the link is restored. Given clocks of high precision at the nodes, the network should be able to operate in this manner for long periods without buffer overflow or depletion.

2. Discrete-Control Correction [6,7,8]

In this method, the clocks of the network are brought into synchronism by making periodic corrections to their frequencies. The correction to each clock is proportional to the change in the levels of the buffers at that node from the previous correction. The constant of proportionality is called the correction-gain for that node. It has been shown that so long as the correc-

tion-gain at each node remains within a specified range, the network attains synchronism. The frequency of synchronism is a weighted average of the initial frequencies of the clocks, the weighting depending on the correction-gains used by the clocks. Thus, this is a method of discrete frequency-averaging. It has been shown that in the event of failure of a part of the network, synchronism is automatically achieved in the remaining subnetwork or subnetworks.

3. Independent Clocks [11,12]

In this method, the nodes use clocks of high precision and stability, such as atomic clocks. The clocks operate independently of one another and no attempt is made to correct the slight discrepancies that might exist among them. Hence, this is not a method of synchronization but rather a method of asynchronous operation. The effects of clock discrepancies as well as delay variations in the medium are absorbed in elastic buffers at each node. Owing to the high precision and stability of the clocks, the nodes can operate for long periods despite a slight asynchronism before the buffers have to be reset to prevent their overflowing.

4. Time-Reference Distribution Method [9,10]

In this method, each clock of the network is assigned a unique rank according to its quality and each link of the network is assigned a figure of demerit according to its characteristics. Each node exchanges information on timing, clock-rank and path demerit with each of the nodes directly linked with it. Applying a set of rules to the information received, a node selects itself or one of its neighbors as an "immediate reference". The results are so designed that in normal operation, each node is using, either directly or indirectly, the highest ranking clock in the network as its "ultimate refer-

ence". Thus, all the clocks are able to remain in synchronism with the master-clock. Also, in normal operation, each node receives its time-reference from the master-clock by the path of least demerit. In the case of failure of some of the nodes or links, the rules for reference-selection should operate so as to re-synchronize each surviving connected part of the network with the highest ranking clock in that part of the network.

CHAPTER 3.

CRITERIA FOR THE COMPARISON OF SYNCHRONIZATION TECHNIQUES

This chapter first defines important parameters to be used to compare the four candidate methods described earlier. Then a qualitative comparison table is given along with pertinent remarks.

The parameters deemed important for the comparison of network operation under the different methods of synchronization are:

1. Bit Count Integrity
2. Effect of Delay Variations in the Propagation Medium
3. Security of Timing against External Action
4. Time Reference
5. Monitorability
6. Interoperability
7. Ease of Network Reconfiguration
8. Amount of Information Processed at a Node
9. Survivability

Brief Description of Criteria

1. Bit Count Integrity refers to keeping count of the exact number of bits transmitted/received at each node, so that all bits are accounted for.
2. A variation in the time of propagation between nodes due to "breathing" of the medium manifests itself as a change in the rate of the incoming bit stream as measured by the receiving node. This criterion refers to the effects of this apparent change of frequency on the synchronism of the network.
3. The third criterion refers to the effects on the system due to external

actions. Such actions may take the form of spoofing, jamming, etc.

4. Time Reference refers to the propagation throughout the network of a reference timing from a common source.
5. Monitorability refers to the ability to monitor the status of the network from information exchanged for the purpose of synchronization.
6. Interoperability refers to the ability of a system using a particular synchronization scheme to communicate with other systems using different synchronization techniques.
7. The seventh criterion refers to factors to be considered in making changes in the network structure by addition or deletion of nodes and links.
8. The next item refers to the amount of data processing involved at each node for the purpose of synchronization.
9. The last criterion, from a synchronization viewpoint, refers to the system's ability to survive in case of a failure in a part of the network.

The table which follows compares qualitatively the different techniques along with pertinent remarks. One should note that experimental investigations will be needed to substantiate some of these opinions since quantitative information is not currently available.

The criteria listed above are not necessarily listed in the order of their importance.

CRITERION	MASTER-SLAVE	DISCRETE CONTROL CORRECTION
Bit Count Integrity	Maintained if buffers are large enough to absorb delay variations.	Maintained if buffers are large enough to absorb delay variations.
[Anticipated Buffer Size]	SMALL	MODERATE
Effect of Delay Variations	Model frequency swings with the delay variations depending on the tracking time constant.	Can change the synchronous frequency of operation.
	FAIR	FAIR
Security of Timing against External Action	A given slaving chain can be disrupted by external action.	External action can significantly affect network performance and operating frequency.
	FAIR	POOR
Time Reference	Not available. May be carried as communications overhead.	Not available. May be carried as communications overhead.
Monitorability	Some monitoring possible.	Some monitoring possible.
Interoperability	Only affects the slaving configuration	Good provided only one fixed frequency exists in the overall network.
Ease of network Reconfiguration	GOOD	MODERATE
Amount of Information Processed at a Node	Only needs to track one incoming frequency.	Must consider multiple buffers and weighting factors.
	SMALL	MODERATE
Survivability	Requires post-failure reallocation of slaving chains.	Synchronization maintained in case of failures.

INDEPENDENT-PRECISE CLOCKS	TIME REFERENCE DISTRIBUTION
Not maintained. Buffers must be periodically reset.	Maintained if buffers are large enough to absorb variations. Effects of constant delays are automatically eliminated
MODERATE TO LARGE	SMALL
Can cause buffer overflow or depletion.	Transient delay can be absorbed if sufficiently frequent measurements are taken.
FAIR	GOOD
Robust against external action.	Sophisticated external action may affect the overall network performance.
GOOD	GOOD
Accurate to within the frequency standard available to each node.	Accurate to the best reference in the system within the ability to measure delays.
No monitoring needed for synchronization purposes.	Has capabilities of extensive monitoring.
May increase buffer reset rates and cause loss of bit count integrity.	Buffers may have to be reset at interfaces to other networks.
GOOD	GOOD
Only clock trends and corrections.	Information from all neighbors must be processed for deciding best reference and determining time delays.
SMALL	MODERATE
Failures do not affect the operation of the surviving part of the system.	Path of time dissemination is automatically reallocated to establish a new hierarchy in each of the surviving subsystems.

Bit Count Integrity

Bit count integrity can be maintained in the master-slave mode of operation provided the buffers are large enough to absorb the network delay variation. It is not sufficient to simply absorb variations over links of the slaving structure since communications may take place between nodes which are separated by many links of the slaving hierarchy. This 'whip effect' is one of the dominant considerations in selection of an appropriate buffer size.

In the discrete-control-correction case, the buffers must be sufficiently large to absorb delay variations and the initial frequency offsets of the nodes. Appropriate measures can be taken to remove unwanted steady state contents of the buffers, however, this does not in general affect the buffer sizing considerations.

The independent clock scheme does not in general have the ability to maintain bit count integrity. Any small differences in clock frequencies will eventually cause a buffer to either deplete or overflow which causes a loss of bit count integrity. The only alternative in this case is to reset the buffers at known fixed points in time, thus causing a controllable loss of integrity. The use of very stable clocks and reasonably large buffers should allow such a system to run for extended periods of time before resetting the buffers becomes necessary.

In time reference distribution, only the delay variations between adjacent nodes need be absorbed since all the constant delays can be automatically removed and all nodes can be referenced to a common timing source. Hence, the 'whip effect' as observed in master-slave systems does not arise in the time reference distribution case.

Effects of Delay Variations

The dominant effects of delay variations have been discussed under the heading of bit count integrity. However, there are other effects which must be considered.

In master-slave networks, the nodal frequencies may vary as the time delays change. The magnitude of the frequency variation is proportional to the delay variations and the tracking time constants. In discrete-control-correction, the instantaneous nodal frequencies and the steady state frequency of operation can be affected by delay variations. The effects of delay variations on the precise clock system can be very dramatic since buffer overflow or depletion can occur. Transient delays can be automatically absorbed in time reference distribution systems if measurements of the delays on the individual communication links are made sufficiently often.

Security Against External Action

The independent clock technique is the most robust when considering external action against the synchronization of a network. Since the clocks run independently of the communication links and other network components, they are also independent from external harassment other than being destroyed or partially damaged.

In the case of time reference distribution, very sophisticated techniques would have to be used to alter the messages between nodes which establish the distribution structure and the measurement of link delays.

Discrete-control-correction is the most susceptible to external influence since all incoming information is in general used to determine the frequency of operation. However, much work is yet required to understand the sophisticated interrelationships involved in the determination of operating frequency

under the influence of external perturbations and actions.

The chain of hierarchy in the master-slave technique as well as the frequency of operation can be moderately affected by external action. This situation is usually easy to detect by cross referencing to nodes other than the normal master-slave hierarchy.

Time Reference

Availability of good time reference at a node might be required due to reasons not related to synchronization and might play an important role in the selection of a candidate synchronization technique. In the master-slave and discrete-control-correction schemes, time reference will have to be carried as communications overhead. In the independent clock scheme, it is accurate within the frequency standard available at the node. In time-reference distribution, this is an integral part of the scheme and all nodes have the best reference available in the network.

Monitorability

Dynamic system evaluation and control require that the performance and operation of the network be monitored adequately. In the master-slave scheme, only incoming frequencies can be monitored and it is difficult to estimate and control system performance from this information. In discrete-control-correction, buffer changes are monitored at the correction instants and the possible use of this information for control purposes has to be examined further. Monitoring in the independent clock system is only needed for the purposes of resetting buffers.

In the time-reference-distribution method, the time-delays are monitored and eliminated. All nodes have available a wealth of information (including PTTI) about the rest of the network and this could be used effectively to

dynamically improve system performance.

Interoperability

As the all digital DCS has to operate with/through different communication systems like ATT, TRI-TAC etc., it is expected that the synchronization technique selected should be compatible with the schemes used in other systems. This particular criterion can be looked at in different levels as follows. Can the system with a particular synchronization scheme, interoperate with a different one on a

(i) communications level?

(ii) synchronization level?

(i) Interoperability is assured as long as sufficiently large buffers are used for interfacing to ensure bit count integrity.

(ii) In the master-slave method interoperability only affects the slaving configuration as there can only exist a unique master/slave hierarchy. In the discrete-control-correction method as long as only one fixed frequency is available interoperability is ensured. In the independent clock method interoperability is assured but may increase buffer reset rates. Time-reference-distribution may have to default to independent clocks if synchronization information is unavailable from other systems.

Ease of Network Reconfiguration

The addition or deletion of new nodes and links to the network causes no particular problems in any of the synchronization schemes. In the master-slave method, a new node has to be assigned a reference node that it should slave itself to. In the time-reference method, the new node should be assigned its proper rank and the new links should be assigned their proper demerits. The selection and decision rules then operate so as to disseminate the time-ref-

erence to each node from the master node by the best path in the new configuration. With independent clocks, of course, no special action is needed for the addition or deletion of nodes and links. However, in the case of discrete-control-correction, the clock corrections are based on changes in local buffer-levels. Hence, when a link is added/deleted, the contribution of the corresponding buffer should be included/excluded from the calculation of the size of clock-correction. Also, the stable range of the correction parameter decreases with an increase in the number of nodes and this must be taken into account.

Amount of Information Processed to Achieve Synchronization

In the master-slave method each node merely needs to recover the frequency of the particular node it is slaving itself to. In discrete-control-correction the only information that is used is the level of the local buffer. With independent clocks, no clock corrections are sought to be made and the occurrence of overflow or depletion in the buffers is the information used to reset the buffers.

In the time-reference method, each node acquires information from each of its neighbors and processes it as set forth in the selection and decision rules to arrive at a reference node for use over the next period.

Survivability

When there is a failure of a part of the communication network it is possible to ensure, in all the schemes of synchronization, that each of the surviving parts of the network continues to operate as an independent network. In the case of the master-slave technique, this is accomplished by providing each node with a series of back-up references to use in case of progressive failures in the rest of the network. In the case of precise clocks, of course, each node operates as long as it survives regardless of the condition of the other

nodes. In both Discrete-Control-Correction and the Time-Reference Method, the operating procedure automatically ensures that each surviving part of the network continues to operate as an independent network.

Failures in the network can be caused by many factors such as enemy attack, equipment breakdown, etc.

CHAPTER 4.

INTERPRETATION OF THE COMPARATIVE STUDY

The attributes considered essential for the Defense Communication Network were set forth in Chapter 1. A set of performance criteria was discussed in Chapter 3 and a broad comparison of the four techniques was presented in tabular form. The information collected there is now examined to determine the most promising directions for further investigation.

Security form hostile electronic measures such as jamming and spoofing is of the utmost importance in the Defense Communications Network. Moreover, in the event of a partial failure or destruction of the network, the surviving portions of the network should continue their operation. These two features, viz., resisting external electronic interference and carrying on operation in the surviving parts of the network in case of partial failure, were included in the attribute of 'endurance', which appears first in the list of essential attributes. In the event of a partial failure of the network, the continued operation of the surviving parts is assured in all the synchronization methods, as seen from the Comparison Table in Chapter 3. However, as regards the effects of hostile electronic measures on the timing of the nodes, the Comparison Table shows the method of Independent Clocks to be the least vulnerable. Hence, this method affords the best 'endurance', and, for this reason alone, would appear to be the method to adopt for at least the major portion of the network. This view, however, may have to be qualified by a 'monitorability' consideration that is discussed later.

The Defense Communications System should interoperate with other communication networks using other methods of operation. However, the Comparison Table

shows no significant differences among the techniques in this respect, and hence this is not a decisive criterion for comparison.

The third requirement, that the state of the Defense Communication Network should be monitorable from the information that is used to achieve timing synchronization, is of great practical importance. This aspect of system operation was not pursued as part of this study. However, the Time Reference Distribution method appears to have the greatest potential in this regard. In this method, each node collects a wealth of information from all its neighbors regarding their timing, clock references and the propagation time of the transmission paths. This information presents the possibility that tests can be devised to determine the state of the network, and, in particular, to detect the presence of external interference. If such interference is detected, the network can always fall back on the independent clock mode of operation and thus counter the hostile action. In our opinion, the development of such monitoring capabilities will render the Time Reference Distribution method superior to the Independent Clock technique. In normal operation, the Time Reference Distribution method provides an accurate time reference throughout the network without the use of highly precise clocks at all the nodes. In the method of Independent Clocks, the timing of the nodes is secure against hostile interference, but there seems to be little prospect of detecting such interference. If, on the other hand, the information that is available in the Time Reference Distribution method can be used to detect external interference, the system can change to the secure mode of Independent Clocks, with the additional advantage of being aware of hostile interference.

The foregoing arguments point to a choice between the method of Independent Clocks and the Time Reference Distribution techniques for at least the

major portion of the Defense Communications System. The monitorability aspect of the Time Reference Distribution method should be investigated further from the viewpoint of detecting the presence of interference. The results of such an investigation would bear on the final choice of a synchronization technique.

With respect to economy, the choice is influenced by the relative cost of a large number of precise clocks in the method of Independent Clocks and the cost of information processing and the implementation of associated logic in the Time Reference Distribution method. It is recommended that a study be conducted on possible alternative implementations of the Time Reference Distribution method so that this aspect of the problem is clarified.

CHAPTER 5.

RULES FOR PATH SELECTION IN TIME REFERENCE DISTRIBUTION

The need to provide precise time and time interval (PTTI) information throughout networks is growing at a rapid pace [13]. The application of PTTI to navigation and the synchronization of digital communication networks is placing increasing demands on the accuracy of PTTI systems. The use of very precise clocks [14] cannot, in itself, meet these demands unless all the clocks in a network are referenced to some common time source. One method for accomplishing this is to specify a hierarchical structure for the dissemination of PTTI by the "Transfer Standard" technique [15]. However, fixed structure techniques are not easily applied to an operational environment where clock failures and communication link outages must be accomodated.

An alternative approach is to construct a self organizing clock system which dynamically allocates the path over which PTTI information is transmitted [16]. Self organization is accomplished by assigning to each nodal clock a unique rank and to each link a given demerit and then providing a set of rules which decide, on a node by node basis, over which link a node should accept the PTTI information. The merits of this approach have been extensively discussed by Stover [17]. Techniques for implementing this approach have worked exceedingly well in the initial organization of the nodal clock systems. However, after a system failure or perturbation, the network may not reorganize itself.

Presented in this report is a modification of the self organizing clock approach [1] which organizes the system under all initial conditions and perturbations. Furthermore, when in an organized state, each node knows its

position from the selected master in the tree structure used to disseminate PTTI information.

Network Organization Technique

The technique described below is designed to iteratively determine the best path for information dissemination in a hierarchical network structure. Each node of the network is assigned a unique rank which could represent, for example, the relative quality of the node. Each bilateral link between nodes is assigned a demerit which reflects the quality of the interconnection. The object of allocating a unique path through the network is to pass information from the best node to the rest of the nodes over the path of least demerit. Since more than one path may have the same link demerit, uniqueness is guaranteed by selecting the path of minimum demerit via the highest ranking neighboring node.

The process of establishing a network path relies on each node conveying to its connected neighbors its rank, the rank of the node it is using as its ultimate reference, the demerit of the path to its ultimate reference and a nodal update counter. A set of tentative Selection Rules [16] can then be used at each node to decide from where a given node will select its reference, what its ultimate reference will be and the corresponding path demerit to the ultimate reference. These selection rules are used to decide on a unique path of least demerit. Furthermore, they are sufficient by themselves to cause an initial organization of the network if applied iteratively, if all the nodes are initially on self-reference. However, the selection rules are not sufficient to guarantee the reorganization of the network after some perturbation of the network structure.

In order to guarantee that the network will organize itself under all

conditions (in particular, reorganize itself after a perturbation), a set of Decision Rules are used to decide if a given node should use the selected best tentative reference or if it should reference itself. The decision rules operate primarily on information provided by the nodal update counters.

It will be shown that the set of rules consisting of the tentative Selection Rules and the Decision Rules are sufficient to guarantee that the network will organize itself under all circumstances.

Each iteration of the process consists of a transmission of information between directly connected nodes, a selection process and a decision process. We assume that all these processes occur in the time interval between the k^{th} and (k+1)st iterations. Hence, each node obtains its information for the (k+1)st iteration from the information available at the k^{th} iteration.

Notation

The nodes are numbered uniquely between 1 and n where n is the total number of nodes in the network. Furthermore, let r_i be the rank of the clock at node i. The higher the rank, the lower the numerical value of r_i. The nodal clock ranks must be uniquely defined.

The following variables are defined for each node i and for a given iteration k.

$s_i(k) \triangleq$ rank of the clock which node i uses as an ultimate reference between the k'th and (k+1)st iterations.

$\mu_i(k) \triangleq$ the node which node i uses as its immediate reference between the k'th and (k+1)st iterations.

$d_{ij}=d_{ji} \triangleq$ the demerit assigned to the communications link between nodes i and j when such a link exists. The larger the numerical value, the worse the link.

$D_i(k)$ $\triangleq$ the total path demerit by which node i received the ultimate reference it uses between the k'th and (k+1)st iterations.

$T_i(k)$ $\triangleq$ the update counter at node i for the period between the k'th and (k+1)st iterations.

C_i $\triangleq$ the set of all nodes which are directly linked to node i. This set does not contain the node i itself.

Note: Symbols which are modified by a ^ indicate a tentative value for that variable, i.e., $\hat{s}_i(k)$, $\hat{\mu}_i(k)$ and $\hat{D}_i(k)$.

Selection Rules

There are three basic rules which are used to decide the best tentative reference for a node to use. These rules are applied sequentially to determine the best tentative reference to use between the (k+1)st and the (k+2)nd iterations based on the information available between the k'th and (k+1)st iterations. If a given rule uniquely determines the best tentative reference, the remaining rules are not applied. Once the best tentative reference is determined a set of decision rules are used to specify whether the best or an alternative reference is actually used.

Rule S1 Let $\hat{s}_i(k) = \min\{r_i, \min_{j \in C_i} s_j(k-1)\}$ $\quad i = 1, \ldots.., n$

a) if $\hat{s}_i(k) = r_i$, then $\hat{\mu}_i(k) = i$ and $\hat{D}_i(k) = 0$.

b) otherwise if $\hat{s}_i(k) = s_q(k-1)$, then let $\hat{\mu}_i(k) = q$ and

$$\hat{D}_i(k) = D_q(k-1) + d_{iq} \text{ if q is unique.}$$

Note: Rule 1 fails to decide $\hat{\mu}_i(k)$ uniquely if two or more of the $s_j(k-1)$ terms are equal to the minimum value $\hat{s}_i(k)$ and $\hat{s}_i(k) \neq r_i$. However $\hat{s}_i(k)$ is uniquely determined.

Rule S2 Suppose $j_1, \ldots, j_v$ are the nodes which give a minimum value for $\hat{s}_i(k)$ in Rule 1. Let:

$$\hat{D}_i(k) = \min_{1 \le p \le v} \{d_{ij_p} + D_{j_p}(k-1)\}$$

a) If the minimum is achieved by a unique j_σ, then $\hat{\mu}_i(k) = j_\sigma$

b) Otherwise, apply Rule 3.

Note: Rule 2 fails to decide $\hat{\mu}(k)$ uniquely if two or more paths have the same minimum demerit. However, $\hat{D}_i(k)$ is uniquely determined.

Rule S3 Suppose $j_1, \ldots, j_t$ are nodes which attain the minimum of Rule 2. Suppose that

$$r_{j_q} = \min_{1 \le p \le t} \{r_{j_p}\}.$$

Then let $\hat{\mu}_i(k) = j_q$.

Decision Rules

Once a tentative best reference has been selected by a node, it must decide if it should use that reference. This decision is made using three rules which are applied sequentially. If a given rule is satisfied, the remaining rules are not applied.

Rule D1 If the tentative best reference for a given node i is a self reference, then the node uses itself as a reference and reduces its update counter by one unless its counter is already at zero in which case the counter is left at zero. If this rule applies, then rules D2 and D3 are not applied; i.e.,

a) if $\hat{s}_i(k) = r_i$, then $s_i(k) = r_i$,

$$\mu_i(k) = i,\ D_i(k) = 0 \text{ and } T_i(k) = \begin{cases} T_i(k-1 - 1 & \text{if } T_i(k-1) > 0 \\ 0 & \text{if } T_i(k-1) = 0 \end{cases},$$

b) otherwise, apply Rule D2.

Rule D2 If the received update counter associated with the best tentative reference is smaller than the update counter at the given node i, then the node i uses the best reference received and makes its update counter equal to the received update counter from the best tentative reference incremented by one. If this rule applies, rule D3 is not applied; i.e.,

a) if $T_{\hat{\mu}_i(k)}(k-1) < T_i(k-1)$, then $\hat{s}_i(k) = s_i(k)$,

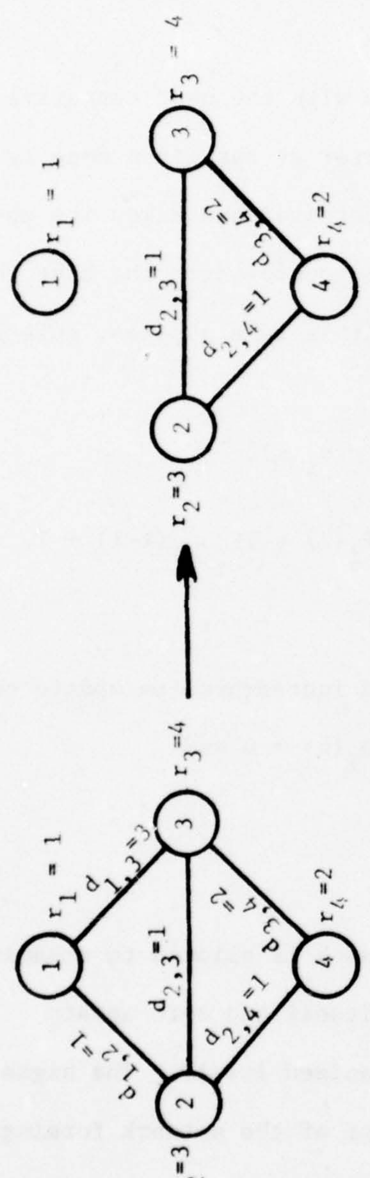
$$\mu_i(k) = \hat{\mu}_i(k),\ D_i(k) = \hat{D}_i(k) \text{ and } T_i(k) = T_{\hat{\mu}_i(k)}(k-1) + 1,$$

b) otherwise, apply Rule D3.

Rule D3 The node i uses itself as a reference and increments its update counter by one; i.e., $s_i(k) = r_i$, $\mu_i(k) = i$, $D_i(k) = 0$ and $T_i(k) = T_i(k-1) + 1$.

Example

Shown in Fig. 1 is a simple 4 node example which is allowed to organize from initial conditions of each node referencing itself and zero update counters. After 5 iterations the network has organized itself. The highest ranking node, node 1, is then severed from the rest of the network forming two subnetworks. The larger subnetwork then reorganizes itself in an additional 6 iterations.



k	s_1	μ_1	D_1	T_1	s_2	μ_2	D_2	T_2	s_3	μ_3	D_3	T_3	s_4	μ_4	D_4	T_4
0	1	1	0	0	3	2	0	0	4	3	0	0	2	4	0	0
1	1	1	0	0	3	2	0	1	4	3	0	1	2	4	0	0
2	1	1	0	0	1	1	1	1	1	1	3	1	2	4	0	0
3	1	1	0	0	1	1	1	1	4	3	0	2	2	4	0	1
4	1	1	0	0	1	1	1	1	1	2	2	2	2	4	0	2
5	1	1	0	0	1	1	1	1	1	2	2	2	1	2	2	2

ORGANIZED

k	s_1	μ_1	D_1	T_1	s_2	μ_2	D_2	T_2	s_3	μ_3	D_3	T_3	s_4	μ_4	D_4	T_4
6	1	1	0	0	3	2	0	2	1	2	2	2	1	2	2	2
7	1	1	0	0	3	2	0	3	4	3	0	3	2	4	0	3
8	1	1	0	0	3	2	0	4	4	3	0	4	2	4	0	2
9	1	1	0	0	2	4	1	3	2	4	2	3	2	4	0	1
10	1	1	0	0	2	4	1	2	2	4	2	2	2	4	0	0
11	1	1	0	0	2	4	1	1	2	4	2	1	2	4	0	0

REORGANIZED

Fig. 1 Organization and Reorganization Example.

CHAPTER 6.

PROOF OF NETWORK ORGANIZATION UNDER THE SELECTION AND DECISION RULES

Before any of the techniques for synchronization could be considered in a competitive manner, the basic operational feasibility of the methods must be clearly demonstrated. In fact, all the methods except the time reference distribution path selection rules were well established and documented previous to this study. Therefore, the rules given in Chapter 5 were written so as to facilitate a proof that the network would organize itself under all operating conditions.

In the future, better rules or techniques may be formulated which provide a better means for the path selection problem. However, our purpose here is to demonstrate that at least one such method exists, thereby placing this technique on an equal footing for the purpose of this evaluation study. The rest of this Chapter is a proof that a network will organize itself under the rules of Chapter 5.

<u>Theorem</u>

Under the rules given above:

(a) the highest ranking node in the network will become the ultimate reference for all the nodes of the network in a finite number of steps;

(b) this reference will be propagated to each node over a path of minimum demerit from the master node;

(c) if some nodes and links are removed from the network, the highest ranking clock in each surviving subnetwork will become the ultimate reference for that subnetwork, transmitting its reference over a path of minimum demerit to each node.

The proof of this theorem will be developed through several propositions and lemmas.

Proposition I

When a node v is removed from the network, all references to that node disappear from the network in a finite number of steps; i.e., even if some nodes were using v as their ultimate reference, there will be none doing so after a finite number of steps.

Let node v be removed from the network at $k = 0$. Let $M(k) \triangleq \{i: s_i(k) = r_v\}$, i.e., the set of nodes which accept node v as the ultimate reference at k'th step, $k \geq 0$. If $M(k)$ is not the empty set, let $T_{min}(k) \triangleq \min_{i \epsilon M(k)} T_i(k)$.

Lemma 1-a

If $M(0), M(1), \ldots, M(k), M(k+1) \ldots$, are not empty, then

$$T_{min}(0) < T_{min}(1) < \ldots < T_{min}(k) < T_{min}(k+1) < \ldots;$$

i.e., $T_{min}(k+p) \geq T_{min}(k) + p$, for $k, p \geq 0$.

Proof of Lemma 1-a

Consider $M(1) = \{i: s_i(1) = r_v\}$, the set of nodes which accept r_v as their ultimate reference at $k = 1$. Since node v is not in the network, each such node i must have accepted node v as the ultimate reference from some other node $j \epsilon M(0)$. Hence, by rule D2, it must have set its counter $T_i(1)$ equal to $T_j(0) + 1 > T_{min}(0)$. Thus, for each $i \epsilon M(1)$, $T_i(1) > T_{min}(0)$, and therefore $T_{min}(1) > T_{min}(0)$, or $T_{min}(1) \geq T_{min}(0) + 1$.

Clearly, this argument may be repeatedly used to show that

$$T_{min}(k+p) \geq T_{min}(k) + p, \text{ for all } k, p \geq 0.$$

Lemma 1-b

If $i \epsilon M(k)$ (i.e., $s_i(k) = r_v$) and $T_i(k) = T_{min}(k)$, then $s_i(k+p) \neq r_v$

for $p \geq 1$; i.e., any node using node v as the ultimate reference, with its counter equal to the minimum of the counters of all such nodes, does so exactly once.

Proof of Lemma 1-b

Suppose, on the contrary, that $T_i(k) = T_{min}(k)$ and $s_i(k+p) = r_v$, $p \geq 1$. This implies that there exists a node $j \in M(k+p-1)$ such that

$$T_j(k+p-1) < T_i(k+p-1) \tag{1}$$

An examination of the Decision Rules given above shows that, at each node, the counter can increase by at most one at each step. Hence

$$T_i(k+p-1) \leq T_i(k) + p-1 = T_{min}(k) + p-1.$$

Thus, from (1),

$$T_j(k+p-1) < T_{min}(k) + p-1. \tag{2}$$

However, by lemma 1-a,

$$T_j(k+p-1) \geq T_{min}(k+p-1) \geq T_{min}(k) + p-1,$$

and hence

$$T_j(k+p-1) \geq T_{min}(k) + p-1$$

which contradicts (2). This proves Lemma 1-b.

Proof of Proposition I

It follows directly from Lemma 1-b that at each $k \geq 0$, if the set $M(k)$ is not empty, there is at least one node in the network which drops node v as its ultimate reference for all later k. Since the number of nodes is finite, it follows that in a finite number of steps all reference to node v will have disappeared from the network.

Proposition II

Suppose that at $k = 0$, the ultimate reference used by each node in the

network corresponds to some node actually in the network. Then, in a finite number of steps, the highest ranking node will become the ultimate reference for all the nodes of the network. Furthermore, its reference is propagated to each node by a path of minimum demerit.

Proof of Proposition II

The reference-selection rules S1-S3 given above, define for each node i in the network, a unique path of minimum demerit from that node to the master-node, and the corresponding demerit G_i. Hence, the following definition is unambiguous:

let $P_m \triangleq$ the set of nodes for which the above path of minimum demerit to the master-node consists of exactly m links, m = 0, 1, 2, ...,

with P_0 = {the master-node, say, node 1}.

It is obvious that each node in P_{m+1} is directly linked to at least one node in P_m, m = 0, 1, 2, ...

(i) Under the hypothesis of this proposition and the given rules, the master node will always remain on self reference; moreover, in a finite number of steps its counter will be set to zero and will remain at zero thereafter.

Let this be the state at k = 0. Hence

$$\left.\begin{aligned} s_1(k) &\equiv r_1 \\ D_1(k) &\equiv 0 \\ T_1(k) &\equiv 0 \end{aligned}\right\} \qquad k \geq 0$$

Consider a node $j \varepsilon P_1$. It is directly linked to the master node and this direct link is also the path of minimum demerit to the master node.

Hence, for all j P_1, $$\left.\begin{array}{l}\hat{s}_j(k) \equiv r_1 \\ D_j(k) \equiv d_{j1} = G_j\end{array}\right\} \quad k \geq 1.$$

Applying the rules at k = 1,

if $T_j(0) > 0$, then $$\left.\begin{array}{l}s_j(1) = \hat{s}_j(1) = r_1 \\ D_j(1) = \hat{D}_j(1) = G_j \\ T_j(1) = T_1(0) + 1 = 1\end{array}\right\} ,$$

and hence, in fact, $$\left.\begin{array}{l}s_j(k) = \hat{s}_j(k) = r_1 \\ D_j(k) = \hat{D}_j(k) = G_j \\ T_j(k) = T_1(k-1) + 1 = 1\end{array}\right\} k \geq 1.$$

If, however, $T_j(0) = 0$, then $$\begin{array}{l}s_j(1) = r_j \\ D_j(1) = 0 \\ \\ T_j(1) = T_j(0) + 1 \\ \qquad = 1 > T_1(1)\end{array} \quad ;$$

hence, we have, as above, $$\left.\begin{array}{l}s_j(k) = \hat{s}_j(k) = r_1 \\ D_j(k) = \hat{D}_j(k) = G_j \\ T_j(k) = T_1(k-1) + 1 = 1\end{array}\right\} k \geq 2. \qquad (3)$$

Hence, in either case, for $j \varepsilon P_1$, the conditions (3) hold for $k \geq 2$.

(ii) Assume, as the induction hypothesis, that there exists a finite k, say k_m such that for all $j \varepsilon P_m$, $$\left.\begin{array}{l}s_j(k) \equiv r_1 \\ D_j(k) \equiv G_j \\ T_j(k) \equiv m\end{array}\right\} \quad k \geq k_m.$$

Consider a node $i \varepsilon P_{m+1}$. The path of minimum demerit from i to the master node connects i to some node $j \varepsilon P_m$. Then it follows from the induction hypothesis and the given rules that

$$\left.\begin{aligned} \hat{s}_i(k) &\equiv r_1 \\ \hat{D}_i(k) &\equiv G_i \end{aligned}\right\} \quad k \geq k_m + 1.$$

If $T_i(k_m) > m$, then

$$\left.\begin{aligned} s_i(k) &= \hat{s}_i(k) = r_1 \\ D_i(k) &= \hat{D}_i(k) = G_i \\ T_i(k) &= m + 1 \end{aligned}\right\} \quad k \geq k_m + 1.$$

If, on the other hand, $0 \leq T_i(k_m) \leq m$, then

$$\left.\begin{aligned} s_i(k_m + 1) &= r_i \\ D_i(k_m + 1) &= 0 \\ T_i(k_m + 1) &= T_i(k_m) + 1 \end{aligned}\right\}$$

Repeated application of the rules shows that, in any case, $T_i(k_m + m + 1) > m$, and hence for all $i \varepsilon P_{m+1}$,

$$\left.\begin{aligned} s_i(k) &\equiv r_1 \\ D_i(k) &\equiv G_i \\ T_i(k) &\equiv m + 1 \end{aligned}\right\} \quad k \geq k_{m+1},$$

where $k_{m+1} \triangleq k_m + (m+1) + 1 = k_m + m + 2$.

Thus, the induction hypothesis on P_m implies similar properties for P_{m+1}. Since the hypothesis has been verified for P_1, the proof of Proposition II is complete.

Proof of Theorem

The proof of the main theorem may now be stated as follows:

Proposition I shows that, whatever the initial state of the network may

be, it changes within a finite number of steps so as to satisfy the assumptions of Proposition II. Hence, the conclusions of Proposition II, which are the conclusions of the theorem, are established for all initial conditions. In particular, this also proves that in the event of the loss of some nodes and links, each of the surviving subnetworks independently attains the steady-state conditions described in the theorem.

CHAPTER 7.

RANDOM TEST NETWORK GENERATOR

In the precess of developing the path selection rules of Chapter 5, it became apparent that some method for comparing different alternative rules was required. Simulation techniques were the only available methods which could be used to quickly compare the performance of given alternative rules. It was then necessary to construct networks which could be simulated by programs which implemented the appropriate rules.

A set of 480 randomly generated test networks were generated using the program listed in the "Computer Programs" Appendix. The networks generated range from very sparsely interconnected structures to ones with a moderate number of interconnections (links). This large data base of networks was used to verify that the basic simulator programs were operating correctly and to gather statistics on the performance of the different simulators.

The networks were generated in groups having the same number of nodes and bilateral communication links. Networks with 10 nodes have either 10, 15, 20, 25 or 30 links; networks with 15 nodes have either 15, 20, 25 or 30 links; and networks with 20 nodes have either 20, 25 or 30 links. Forty networks were generated in each group.

A program for listing the networks in the data base is also given in the Appendix.

Figs. 2 and 3 are the flow charts for the network data base generator program and the network data base listing program. Fig. 4 is an example listing of two test networks.

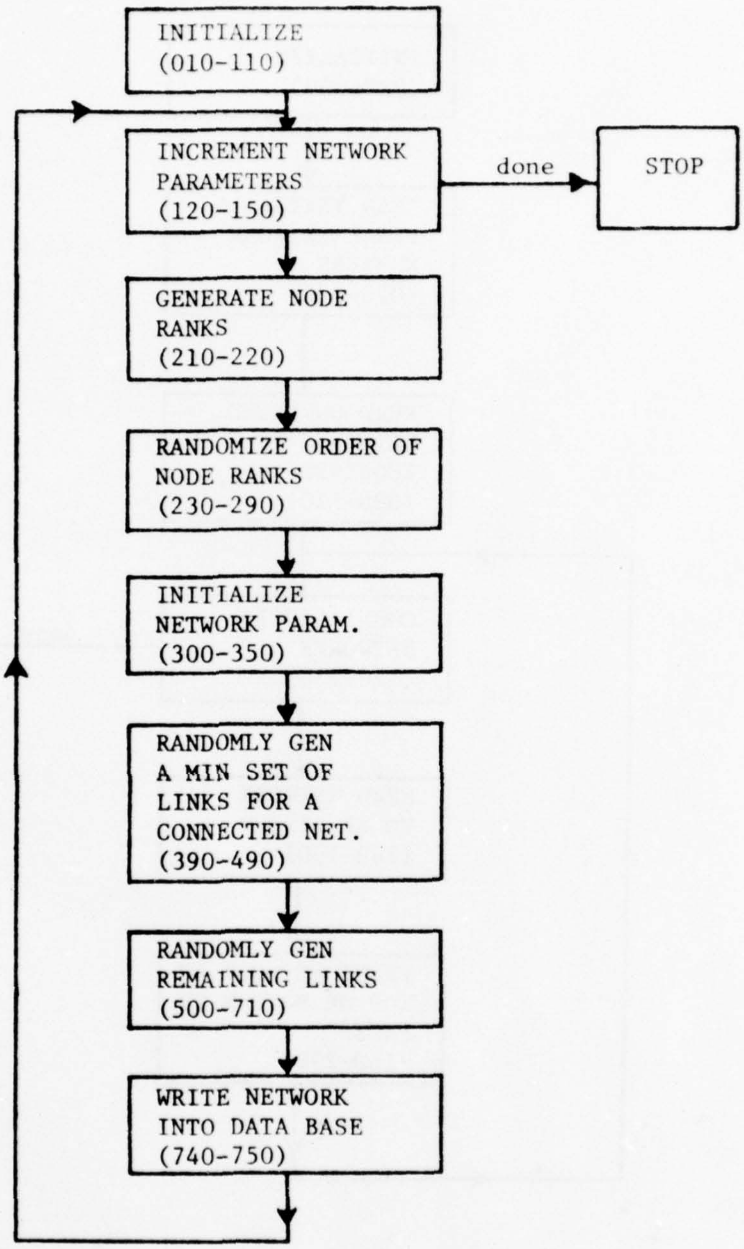


Fig. 2. Flow Chart for the Random Network Data Base Generator

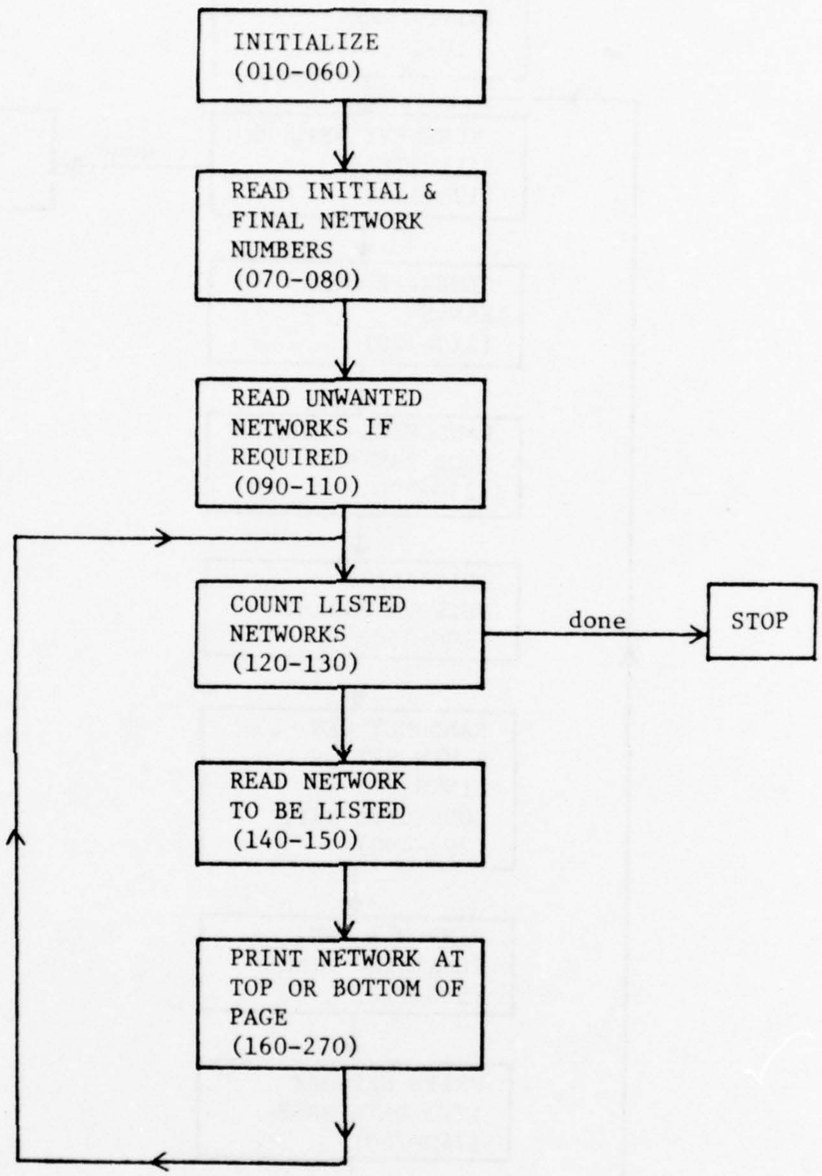


Fig. 3. Flow Chart for the Random Network Data Base Lister.

PROBLEM 335, NODES = 15, LINKS = 30

NODE#	RANK	(LINKED TO NODE/PATH DEMERIT)					
1	2	2/29	4/28	5/28	12/7	6/30	8/2
2	3	1/29	3/14	7/16	8/6	13/19	12/2
3	15	2/14	6/22	9/27	15/12	10/14	11/17
4	10	1/18	10/9	7/7	6/28	15/18	
5	9	1/28	11/5	10/23	14/28		
6	14	3/22	4/28	7/7	1/30	12/9	9/19
7	11	2/16	4/7	15/24	9/8	6/7	
8	13	2/6	1/2				
9	5	3/27	7/8	6/19			
10	4	4/9	14/4	5/23	3/14		
11	8	5/5	3/17				
12	7	1/7	2/2	6/9	15/8		
13	1	2/19					
14	12	10/4	5/28				
15	6	3/12	7/24	12/8	4/18		

PROBLEM 336, NODES = 15, LINKS = 30

NODE#	RANK	(LINKED TO NODE/PATH DEMERIT)					
1	12	2/28	4/2	8/24	7/1	9/5	
2	2	1/28	3/27	6/21	14/27	15/15	5/18
3	8	2/27	10/9	12/8	14/23		8/17
4	10	1/2	5/9	15/29		13/30	
5	14	4/9	10/12	2/18			
6	5	2/21	7/9	9/16	14/6		
7	4	6/9	11/1	13/18	1/1	9/10	
8	3	1/24	13/22	3/17			
9	7	6/16	11/2	1/5	7/10	13/5	
10	1	3/9	5/12	13/8			
11	13	7/1	14/14	9/2			
12	6	3/8					
13	9	7/18	14/5	8/22	3/30	9/5	10/8
14	15	13/5	2/27	11/14	3/23	6/6	
15	11	4/29	2/15				

Figure 4. Sample Networks Listed from the Data Base.

CHAPTER 8.

SIMULATIONS OF PATH SELECTION RULES

As previously stated, it is desirable in the Time Reference Distribution technique to dynamically select the best possible path for disseminating network timing information. Initially, only the selection rules of Chapter 5 were used to select an appropriate dissemination path. This approach is satisfactory provided that each node starts from specified initial conditions and no perturbations in the network structure occur. However, if network perturbations are allowed, examples can be constructed which cause these selection rules to fail. In fact, a simple 3-node example is sufficient to demonstrate this problem.

The underlying difficulty with the original selection rules is that references to nodes which have been deleted from the network can remain in effect since the information describing such a reference can be circularly passed back to a given node. Hence, a reference to a node no longer in the network can be maintained.

As an initial attempt to block the circulation of old information, a set of alternative node Resetting Rules (A and B), and a set of alternative node Reset Holding Rules (1 to 5) were proposed.

Resetting Rules

A. A node must revert to self reference whenever:

i) it changes its ultimate reference (unless the change is from self reference),

ii) the node from which it receives its reference changes ultimate reference.

iii) the node from which it was receiving its reference fails or the communication link over which it was receiving its reference fails.

B. A node must revert to self reference whenever:

i) it changes its ultimate reference (unless the change is from self reference),

ii) the communication link over which it was receiving its reference changes.

Reset Holding Rules

After reverting to self reference, a node must maintain its self reference until:

1. A number of synchronization cycles have occurred which is equal to the rank of the node.
2. The node from which it could take its reference has been using the same reference for a number of synchronization cycles which is greater than the magnitude of the maximum difference in rank between itself and all adjacent nodes, the cycles being measured from the point where the original node became self referencing.
3. The node from which it could take its reference has been using the same reference for a number of synchronization cycles which is greater than the magnitude of the difference in ranks between itself and the node from which it receives its reference, the cycles being measured from the point where the original node became self referencing.
4. The node from which it could take its reference has been using the same reference for a number of synchronization cycles which is greater than its nodal rank, the cycles being measured from the

point where the original became self referencing.

5. Either holding rule 3 or holding rule 4 is satisfied.

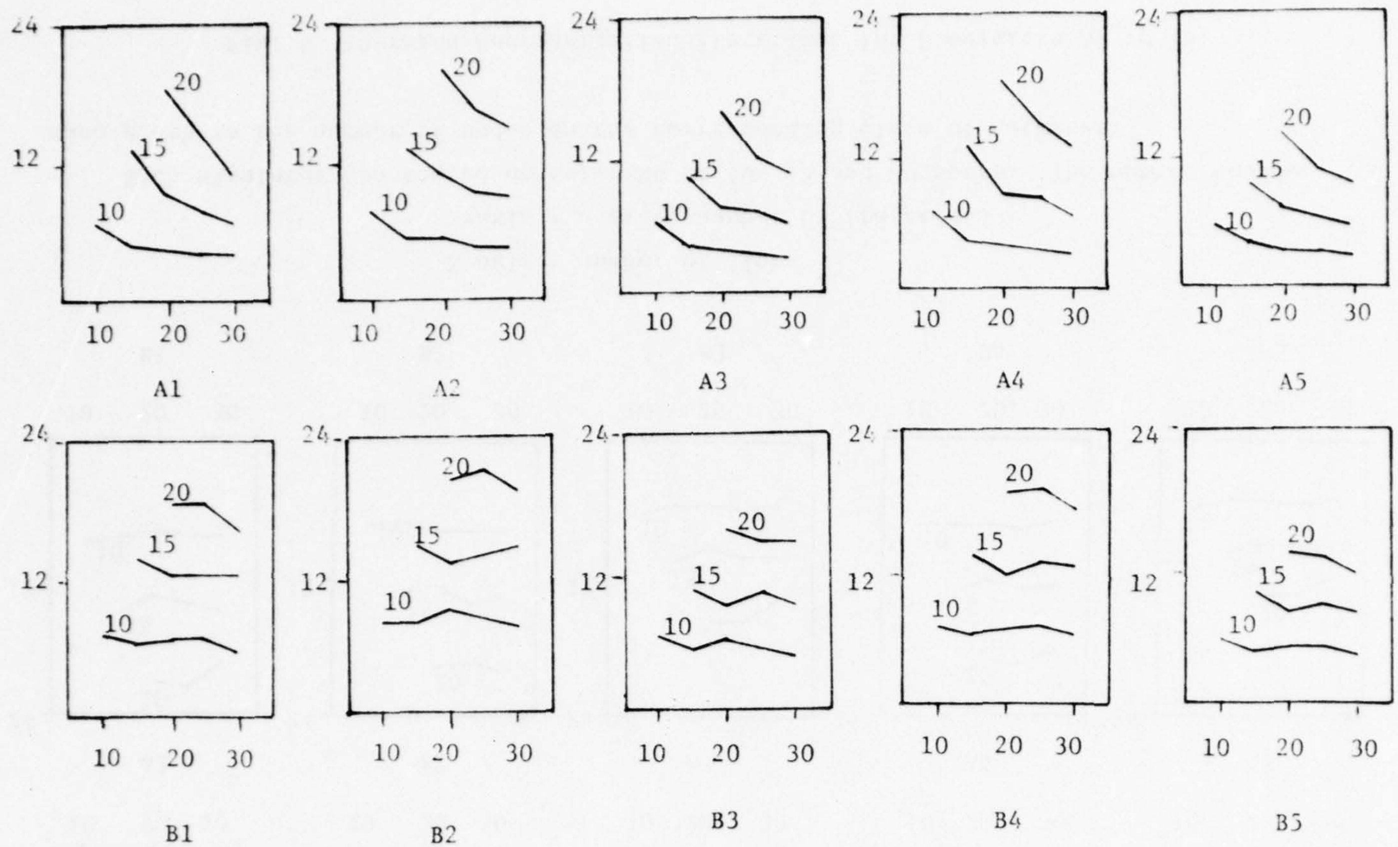
Initial Simulations

Ten simulators (A1 to B5) were constructed to evaluate the performance of the Resetting and Reset Holding Rules. The randomly generated test networks described in Chapter 7 were used to evaluate each simulator program. The number of iterations required for each network to organize itself under the given rules was computed. The best node in each network was then severed from the network and the reorganization process was allowed to proceed. The number of organization and reorganization iterations were averaged for each group of networks in the data base. The averaged organization iterations and reorganization iterations are shown in Figs. 5 and 6 respectively.

These simulations indicate that, for at least the set of networks in the random data base, each alternative method organizes and reorganizes the network properly. However, no insight was gained into a method for explicitly proving that any of these alternative techniques would select an appropriate network path.

The Decision Rule Approach

A simulator was constructed for the final set of Selection and Decision Rules described in Chapter 5. The program used for this simulator and the program for averaging and plotting the results are given in the 'Computer Program' Appendix. The flow chart for the simulator is shown in Fig. 7 and the simulation results in Figs. 8 and 9. These results indicate that these rules perform as well as the previously described rule modifications. However, the decision rule approach has the distinct advantage that proper performance can be demonstrated for all operating conditions.

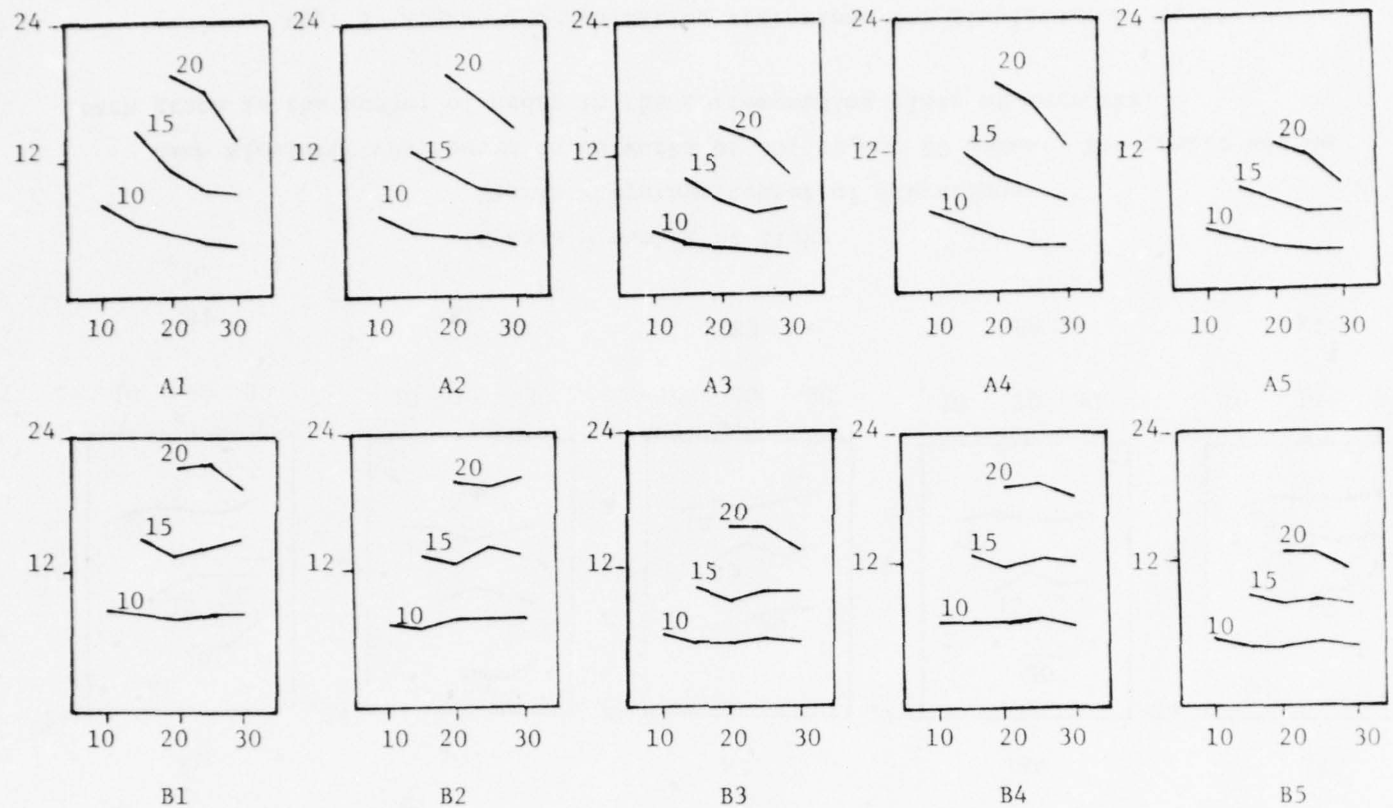


X-axis = number of links

Y-axis = average number of iterations

Each simulator was tested on networks of 10, 15 and 20 nodes. The number beside each graph is the number of nodes in the corresponding class of networks.

Fig. 5 Averaged Organization Iterations for Simulators A1 to B5.



X-axis = number of links

Y-axis = average number of iterations

Each simulator was tested on networks of 10, 15 and 20 nodes. The number beside each graph is the number of nodes in the corresponding class of networks.

Fig. 6 Averaged Reorganization Iterations for Simulators A1 to B5.

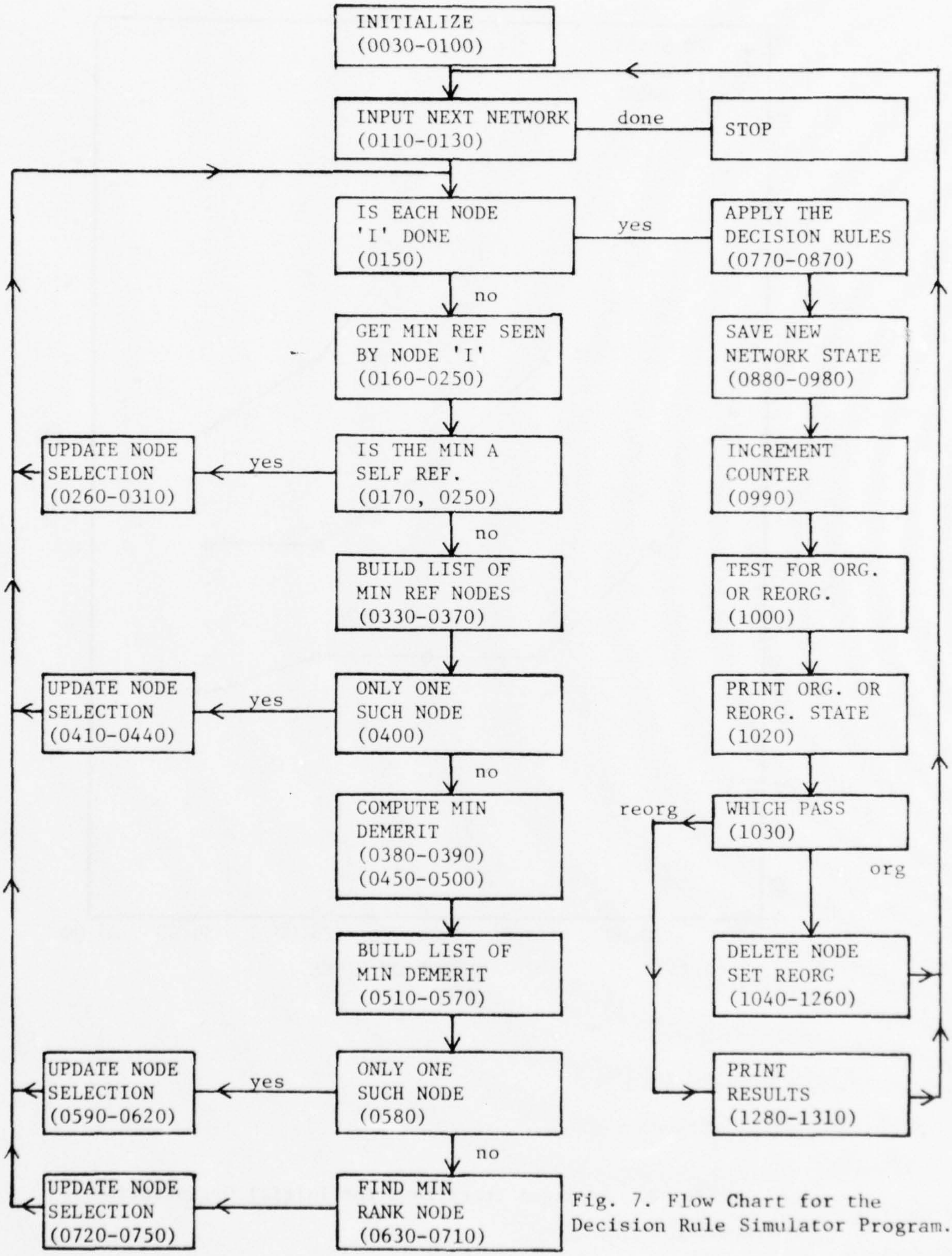


Fig. 7. Flow Chart for the Decision Rule Simulator Program.

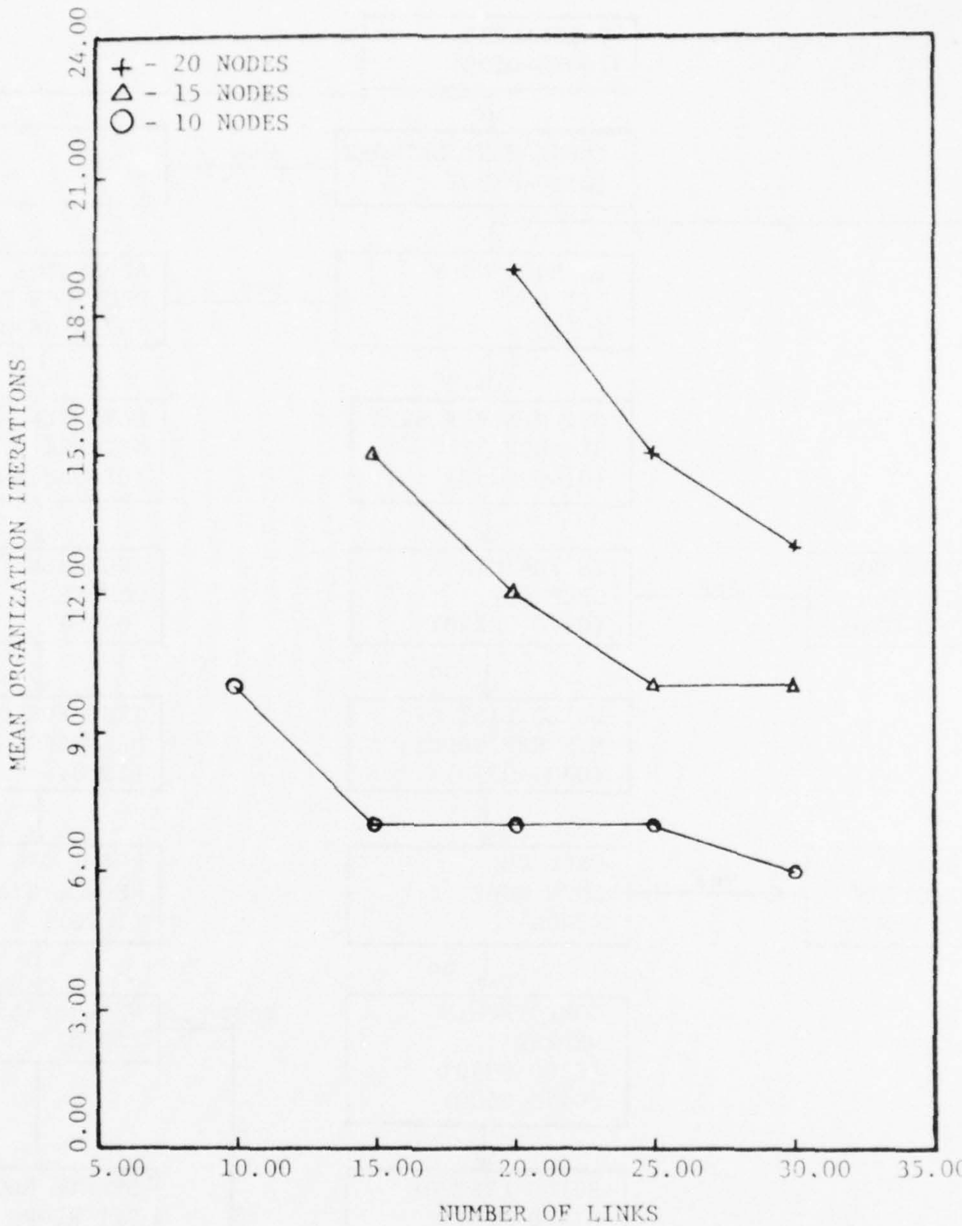


Fig. 8. Averaged Iterations for Initial Organization

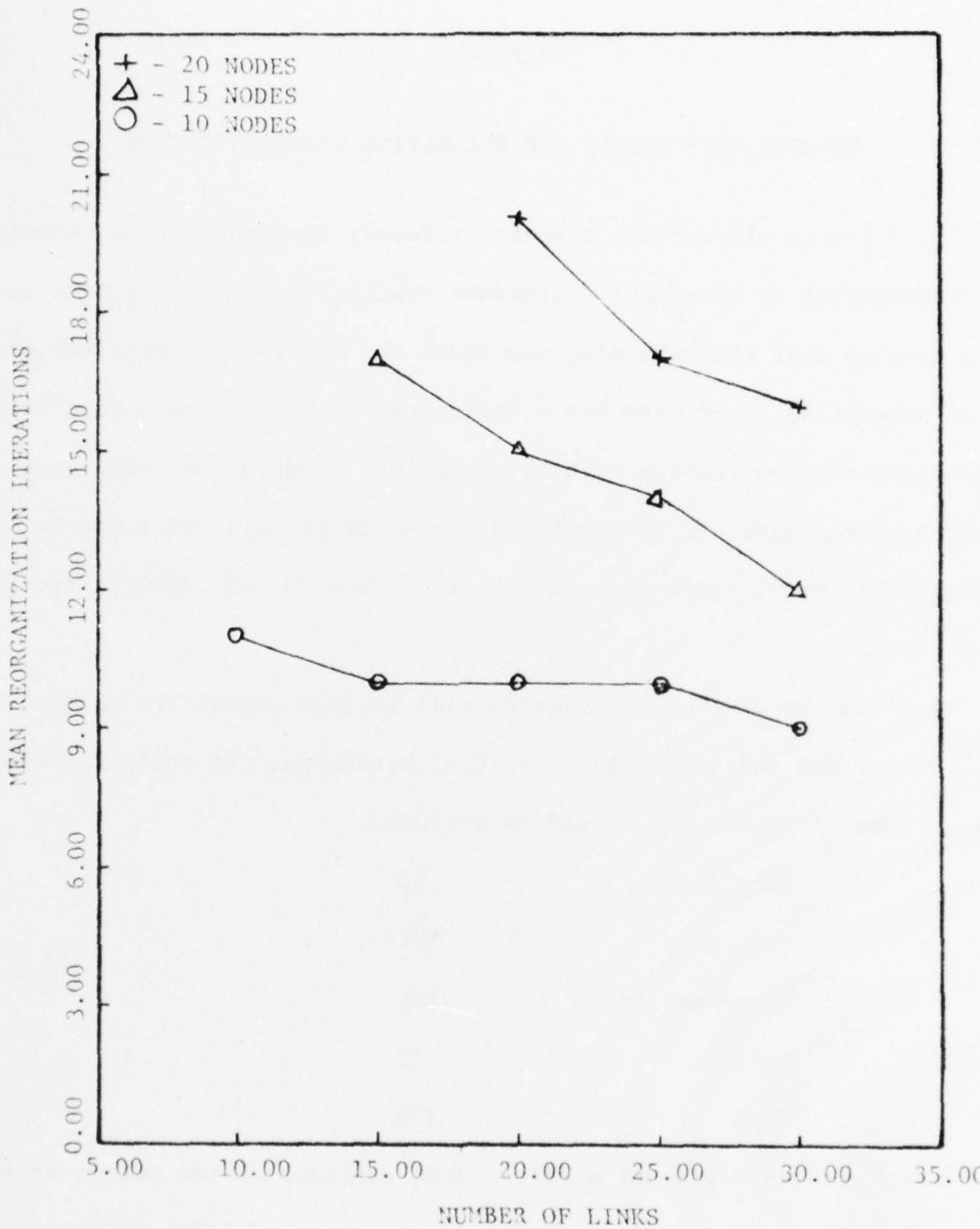


Fig. 9. Averaged Iterations for Reorganization.

CHAPTER 9.

NETWORK TEST MODELS FOR EVALUATING SYNCHRONIZATION

In order to effectively compare different synchronization techniques, it is essential to construct a standard test network. The network used for this purpose must realistically represent the majority of problems encountered in attempting to synchronize a large scale network. Both topological and communications constraints must be presented. Modulation techniques, multiplexing hierarchies and the number of channels per link will not be considered in this model since they do not affect the overall network synchronization problem.

The classes of links considered will include satellite, microwave, troposcatter, radio and wire. As an initial breakdown, the following tentative percentages of link types should be included.

Satellite	8%
Microwave	50%
Troposcatter	10%
Radio	2%
Wire	30%

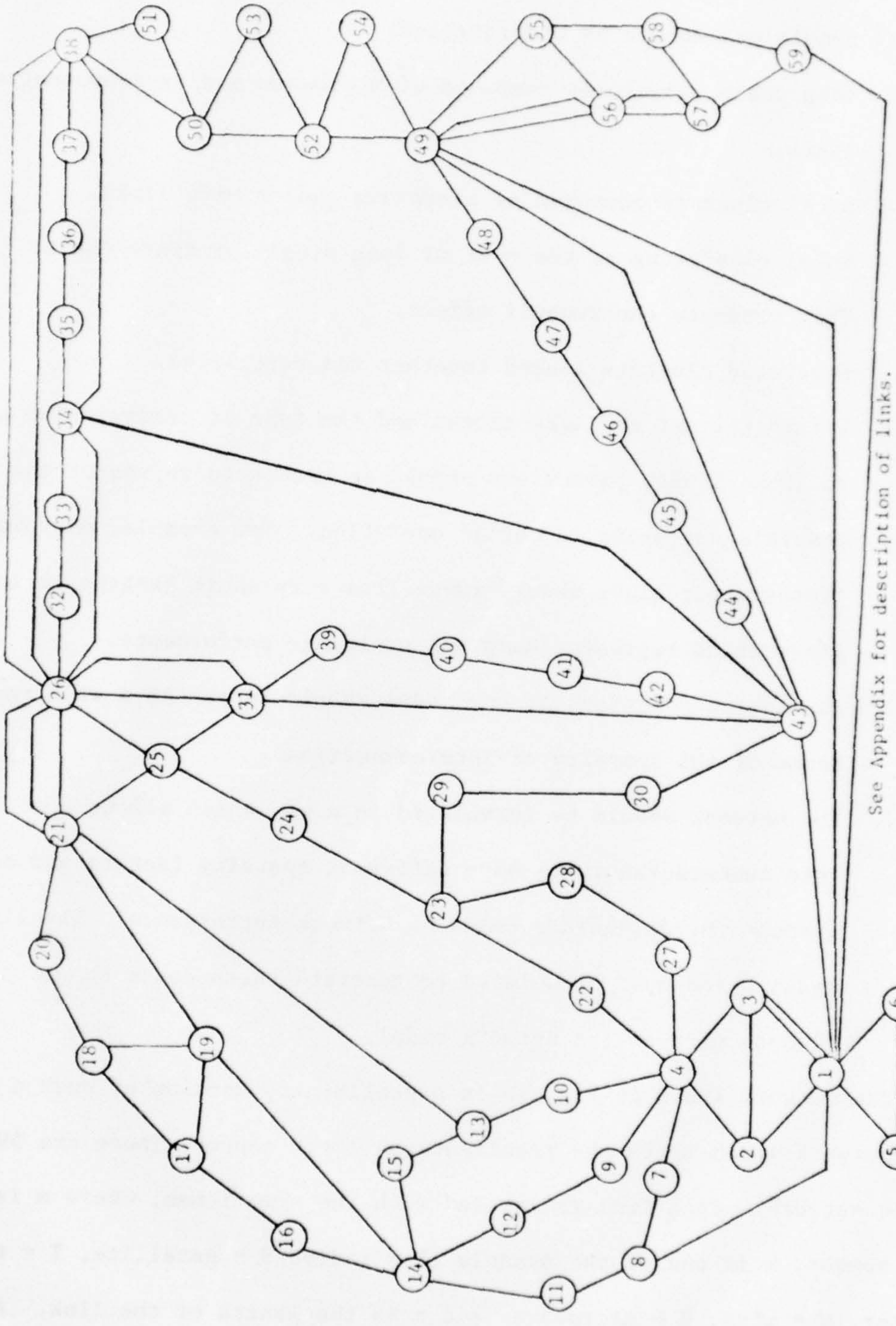
These percentages represent a first crude estimate of the makeup of the future DCS. Since we desire to represent all types of links in our network, the above percentages indicate that a test network should have at least 50 links in order that a minimum of 1 radio link is included on a percentage basis. The number of links in our standard network was arbitrarily chosen to be 100.

The most critical concern in constructing a test model is the con-

straints of the topology of the network. In this regard, the following topological conditions should be incorporated:

1. Long chain structures composed of microwave and/or troposcatter links.
2. Local clusters composed of microwave and/or wire links.
3. Local clustering at the ends of long single or spare chains. This produces the dumbell effect.
4. Separated clusters linked together via satellites.
5. Within the set of links chosen and the type of transmission assigned to those links, parameters should be chosen to represent the widest possible variation in normal operation. For example, microwave and troposcatter links should range from very short lengths to long links which represent marginal or fringe performance.
6. The interconnections at the nodes should represent a wide range in terms of the sparsity of interconnection.
7. The network should be formulated in a way which allows a separation into subnetworks which have different sparsity factors and can represent the degenerate cases of network performance. The links and nodes which must be deleted to generate these cases should be specified as part of the network model.

The network shown in Fig. 10 is a preliminary version of such a standard test network which meets the requirements listed above. There are 59 nodes in the network. Each link is labeled with the symbol mxn, where m is the link number, x is one of the symbols {R = radio, S = satellite, T = troposcatter, W = wire, M = microwave} and n is the length of the link. A listing of the links is given in the 'Standard Test Network' Appendix.



See Appendix for description of links.

Fig. 10. Standard Test Network Configuration.

CHAPTER 10

CONCLUSIONS

In light of the evaluation presented in Chapter 4, the conclusion of this report is that the Time Difference Distribution Technique, with further development of its monitoring capabilities, will best meet the DCS requirements of endurance, inter-operability, monitor ability, and economy of operation. This is particularly true in the situation where the TRD technique is used to provide the backbone timing of a large network.

The Master Slave and Discrete Control Correction Techniques also have their appropriate place in the Defense Communication System. For example, they would be sufficient in a regional or tactical environment where simplicity of operation is essential.

Considerable work remains to be done on the Time Reference Distribution Technique. In particular, one provable set of decision rules have been presented; however, alternative methods should be developed and compared in order to provide the most effective technique. Furthermore, procedures and protocols need to be developed for transmitting information between nodes and for effecting time delay measurements.

Network strategies which can effectively utilize the increased monitorability provided by Time Reference Distribution need to be developed. These strategies should include the evaluation, control, protection, maintenance, repair, and modification of the system.

A study should be made of the algorithms to implement TRD decision rules in terms of hardwired logic or computer programs. This study should also include estimates of the computational capacity necessary to carry out these

algorithms.

An investigation of the sensitivities of the Discrete Control Correction and Time Reference Distribution Techniques to external influences should be performed in order to understand the implication of such influences on system performance and control.

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COMPUTER PROGRAM

APPENDIX

```
C     RANDOM NETWORK GENERATOR FOR DCA SYNCHRONIZATION SIMULATORS  GED00010
C                                                                  GED00020
      IMPLICIT INTEGER*2(1-N)                                      GED00030
      INTEGER*2 B,DDD                                              GED00040
      INTEGER*2 DL                                                 GED00050
      INTEGER*4 N                                                  GED00060
      INTEGER*4 KGET                                               GED00070
      DIMENSION NR(100),NS(100),IS(100),NU(1CC),IU(1CC),NC(1CC,1C),GED00080
     1 ND(100),ID(100),NL(100), DL(100,10), B(1C),NT(1CC),IT(1CC)  GED00090
      N=93521                                                      GED00100
      NPR=C                                                        GED00110
      DC 116 NODES=10,20,5                                         GED00120
      DC 116 LINK=NODES,30,5                                       GED00130
      DC 116 NCCUN=1,40                                            GED00140
      NPR=NPR+1                                                    GED00150
C                                                                  GED00180
C     GENERATE RANDOM NODE CONFIGURATION                           GED00190
C                                                                  GED00200
      DC 101 I=1,NODES                                             GED00210
  101 NR(I)=I                                                      GED00220
      NN=NODES*5                                                   GED00230
      DC 101 I=1,NN                                                GED00240
      J=KGET(N,NODES)                                              GED00250
      K=KGET(N,NODES)                                              GED00260
      NRR=NR(J)                                                    GED00270
      NR(J)=NR(K)                                                  GED00280
  102 NR(K)=NRR                                                    GED00290
      DC 103 I=1,NODES                                             GED00300
      NT(I)=0                                                      GED00310
      NU(I)=I                                                      GED00320
      ND(I)=0                                                      GED00330
      NL(I)=0                                                      GED00340
  103 NS(I)=NR(I)                                                  GED00350
C                                                                  GED00360
C     GENERATE 2-WAY RANDOM LINKS                                  GED00370
C                                                                  GED00380
      DC 106 I=2,NODES                                             GED00390
      II=I-1                                                       GED00400
  104 J=KGET(N,II)                                                 GED00410
      IF (NL(J)-10) 105,104,104                                    GED00420
  105 NL(J)=NL(J)+1                                                GED00430
      NL(I)=1                                                      GED00440
      DDD=KGET(N,LINK)                                             GED00450
      NC(J,NL(J))=I                                                GED00460
      NC(I,1)=J                                                    GED00470
      DL(J,NL(J))=DDD                                              GED00480
  106 DL(I,1)=DDD                                                  GED00490
      IF (LINK-NODES) 115,107,107                                  GED00500
  107 DC 114 I=NODES,LINK                                          GED00510
  108 J=KGET(N,NODES)                                              GED00520
      IF (NL(J)-10) 109,108,108                                    GED00530
```

```
109 K=KGET(N,NODES)                                              GED00540
    IF (NL(K)-10) 110,109,109                                    GED00550
110 IF (K-J) 111,109,111                                         GED00560
111 NW=NL(K)                                                     GED00570
    DC 112 L=1,NW                                                GED00580
    IF (NC(K,L)-J) 112,108,112                                   GED00590
112 CONTINUE                                                     GED00600
    NW=NL(J)                                                     GED00610
    DC 113 L=1,NW                                                GED00620
    IF (NC(J,L)-K) 113,109,113                                   GED00630
113 CONTINUE                                                     GED00640
    DDD=KGET(N,LINK)                                             GED00650
    NL(J)=NL(J)+1                                                GED00660
    NL(K)=NL(K)+1                                                GED00670
    NC(J,NL(J)=K                                                 GED00680
    NC(K,NL(K)=J                                                 GED00690
    DL(J,NL(J))=DDD                                              GED00700
    DL(K,NL(K))=DDD                                              GED00710
114 CONTINUE                                                     GED00720
115 CONTINUE                                                     GED00730
    WRITE (6) NPR,NODES,LINK,NR,NS,NU,ND,NL,NC,DL,NT             GED00740
116 CONTINUE                                                     GED00750
    STOP                                                         GED00760
    END                                                          GED00770
    INTEGER FUNCTIONKGET(N,NN)                                     B00010
    INTEGER*2 NN                                                   B00020
    F=NN                                                           B00030
    KGET=F*RAN(N)                                                  B00040
    KGET=KGET+1                                                    B00050
    RETURN                                                         B00060
    END                                                            B00070
```

```
C      DCA NETWORK SYNCHRONIZATION SIMULATOR
C
       IMPLICIT INTEGER*2(I-N)
       INTEGER*2 B,DDD
       INTEGER*2 DL
       INTEGER*4 N
       INTEGER*4 KGET
       DIMENSION NR(100),NS(100),IS(100),NU(ICC),IL(ICC),NC(1CC,10),
      1 ND(100),ID(100),NL(100),DL(100,10),B(1C),NT(100),IT(1CC)
       WRITE (2,142)
   101 READ (6,END=3434) NPR,NODES,LINK,NR,NS,NL,ND,NL,NC,DL,NT
       NIT=0
       IGC=0
   102 DC 120 I=1,NODES
       M=NR(I)
       NLL=NL(I)
       IF (NLL) 106,106,103
   103 DC 105 J=1,NLL
       NCC=NC(I,J)
       IF (M-NS(NCC)) 105,104,104
   104 M=NS(NCC)
   105 CONTINUE
       IS(I)=M
       L=0
       IF (M-NR(I)) 107,106,106
   106 IU(I)=I
       IS(I)=M
       ID(I)=0
       IT(I)=NT(I)-1
       IF (IT(I).LT.0) IT(I)=0
       GO TO 120
   107 DC 109 J=1,NLL
       NCC=NC(1,J)
       IF (M-NS(NCC)) 109,108,108
   108 L=L+1
       B(L)=J
   109 CONTINUE
       II=NC(I,B(1))
       M=ND(II)+DL(I,B(1))
       IF (L-1) 110,110,111
   110 IU(I)=NC(I,B(1))
       ID(I)=M
       IT(I)=NT(IU(I))
       GO TO 120
   111 DC 113 J=2,L
       II=NC(1,B(J))
       NCC=ND(II)+DL(I,B(J))
       IF (M-NCC) 113,112,112
   112 M=NCC
   113 CONTINUE
       NC=C
       DC 115 J=1,L
```

```
      II=NC(I,B(J))                                                     T2D00530
      IF (M-ND(II)-DL(I,B(J))) 115,114,114                              T2D00540
  114 NC=NC+1                                                           T2D00550
      B(NC)=B(J)                                                        T2D00560
  115 CONTINUE                                                          T2D00570
      IF (NQ-1) 116,116,117                                             T2D00580
  116 IU(I)=NC(I,B(1))                                                  T2D00590
      ID(I)=ND(IU(1))+DL(I,B(1))                                        T2D00600
      IT(I)=NT(IU(I))                                                   T2D00610
      GO TO 120                                                         T2D00620
  117 NE=NC(I,B(1))                                                     T2D00630
      M=NR(NE)                                                          T2D00640
      NP=1                                                              T2D00650
      DC 119 J=2,NC                                                     T2D00660
      NE=NC(I,M(J))                                                     T2D00670
      IF (M-NR(NE)) 119,118,118                                         T2D00680
  118 NP=J                                                              T2D00690
      M=NR(NE)                                                          T2D00700
  119 CONTINUE                                                          T2D00710
      IU(I)=NC(I,B(NP))                                                 T2D00720
      ID(I)=ND(IU(I))+DL(I,B(NP))                                       T2D00730
      IT(I)=NI(IU(I))                                                   T2D00740
  120 CONTINUE                                                          T2D00750
      IFLAG=0                                                           T2D00760
      DC 124 I=1,NODES                                                  T2D00770
      IF (IU(I)-1) 121,124,121                                          T2D00780
  121 IF (NT(I)-IT(1)) 123,123,122                                      T2D00790
  122 IT(I)=IT(I)+1                                                     T2D00800
      GO TO 124                                                         T2D00810
  123 IFLAG=1                                                           T2D00820
      IU(I)=I                                                           T2D00830
      ID(I)=0                                                           T2D00840
      IS(I)=NR(I)                                                       T2D00850
      IT(I)=NT(I)+1                                                     T2D00860
  124 CONTINUE                                                          T2D00870
      DC 131 I=1,NODES                                                  T2D00880
      IF (IGLAG) 125,125,130                                            T2D00890
  125 IF (NU(I)-IU(1)) 129,126,129                                      T2D00900
  126 IF (NS(I)-IS(I)) 129,127,129                                      T2D00910
  127 IF (ND(I)-ID(I)) 129,128,129                                      T2D00920
  128 IF (IT(I)-NT(I)) 129,130,129                                      T2D00930
  129 IFLAG=1                                                           T2D00940
  130 NS(I)=IS(I)                                                       T2D00950
      NT(I)=IT(I)                                                       T2D00960
      NU(I)=IU(I)                                                       T2D00970
  131 ND(I)=ID(I)                                                       T2D00980
      NIT=NIT+1                                                         T2D00990
      IF (IFLAG) 132,132,102                                            T2D01000
  132 NIT=NIT-1                                                         T2D01010
      WRITE (3,143) (NS(I),I=1,NODES)                                   T2D01020
      IF (IGC) 133,133,141                                              T2D01030
```

```
  133 IGC=1                                                         T2D01040
      NIT1=NIT                                                      T2D01050
      NIT=NIT+1                                                     T2D01060
      DC 134 I=1,NODES                                              T2D01070
      IF (NR(I)-1) 134,135,134                                      T2D01080
  134 CONTINUE                                                      T2D01090
  135 NTEST=I                                                       T2D01100
      NLL=NL(NTEST)                                                 T2D01110
      NL(NTEST)=0                                                   T2D01120
      DC 140 I=1,NLL                                                T2D01130
      NCCC=NC(NTEST,I)                                              T2D01140
      NLLL=NL(NCCC)                                                 T2D01150
      DC 136 J=1,NLLL                                               T2D01160
      IF (NC(NCCC,J)-NTEST) 136,137,136                             T2D01170
  136 CONTINUE                                                      T2D01180
  137 IF (J-NLLL) 138,140,140                                       T2D01190
  138 JJ=J+1                                                        T2D01200
      DC 139 K=JJ,NLLL                                              T2D01210
      KK=K-1                                                        T2D01220
      DL(NCCC,KK)=DL(NCCC,K)                                        T2D01230
  139 NC(NCCC,KK)=NC(NCCC,K)                                        T2D01240
  140 NL(NCCC)=NLLL-1                                               T2D01250
      GO TO 102                                                     T2D01260
  141 NIT=NIT-NIT1-1                                                T2D01270
      WRITE (3,144) NPR,NODES,LINK,NIT1,NIT                         T2D01280
      WRITE (2,144) NPR,NODES,LINK,NIT1,NIT                         T2D01290
      GO TO 101                                                     T2D01300
      STOP                                                          T2D01310
C                                                                   T2D01320
C                                                                   T2D01330
  142 FORMAT (49H DCA SYNCHRONIZATION SIMULATOR DATA, CONTROL - T2)T2D01340
  143 FORMAT (IX,3012)                                              T2D01350
  144 FORMAT (5110)                                                 T2D01360
      END                                                           T2D01370
```

```
C     DCA TEST NETWORK LISTER
C
      IMPLICIT INTEGER*2(A-2)
      DIMENSION NR(100),NS(100),IS(100),NU(100),IL(100),NC(1CC,1C),
     1 ND(100),ID(100),NL(100),DL(100,10),B(10),MM(1CC)
      IND=1
      READ (1,110) NIN,NFIN
      NCCUNT=NIN-1
      IF (NCCUNT) 103,103,101
  101 DC 102 I=1,NCCUNT
  102 READ (6,END=3434) NPR,NODES,LINK,NR,NS,NU,ND,NL,NC,DL,MM
  103 NCCUNT=NCCUNT+1
      IF (NCCUNT.GT.NFIN) GO TO 109
      READ (6,END=3434) NPR,NODES,LINK,NR,NS,NU,ND,NL,NC,DL,MM
      GO TO (104,105), IND
  104 IND=2
      WRITE (3,111) NPR,NODES,LINK
      NN=NODES
      GO TO 107
  105 IND=1
      NN=27-NN
      DC 106 I=1,NN
  106 WRITE (3,112)
      WRITE (3,113) NPR,NODES,LINK
  107 DC 108 I=1,NODES
      NLL=NL(I)
  108 WRITE (3,114) I,NR(I),(NC(I,J),DL(I,J),J=I,NLL)
      GO TO 103
  109 STOP
C
  110 FORMAT (213)
  111 FORMAT (  1H1,9X, 8HPRCELEM, 13, 11H, NODES=, 13, 11H, LINKS=
    1 ,13//10X, 11HNCDE# RANK,3X, 29H(LINKED TO NODE/PATH DEMERIT))
  112 FORMAT (  1H )
  113 FORMAT (10X, 8HPRCBLEM, 13, 11H, NODES=, 13, 11H, LINKS=, 13/
    1/10X, 11HNCDE# RANK,3X, 29H(LINKED TO NODE/PATH DEMERIT))
  114 FORMAT (11X,13,4X,12,2X,10(13, 1H/12))
      END
```

```
C     DCA PLOT ROUTINE FOR RANDOM NETWORK ORGANIZATION RESULTS
C
      DIMENSION A(11,5), B(11,5), X(7)
      DIMENSION IBUF(1000)
      DATA X/10.,15.,20.,25.,30.,5.,5./
      DATA A1,A2,B1,B2/0.,3.,0.,3./
  101 CALL PLOTS (IBUF,1000,3)
  102 READ (1,108,END=107) ISYM
      DC 104 JJ=1,12
      READ (1,109) NODES,LINK,MAVS,MAVR
      MINS=MAVS
      MINR=MAVR
      MAXS=MAVS
      MAXR=MAVR
      DC 103 I=2,40
      READ (1,110) M,MM
      MAVS=MAVS+M
      MAVR=MAVR+MM
      IF (M.GT.MAXS) MAXS=M
      IF (M.LT.MINS) MINS=M
      IF (MM.GT.MAXR) MAXR=MM
      IF (MM.LT.MINR) MINR=MM
  103 CONTINUE
      MAVS=MAVS/40
      MAVR=MAVR/40
      N=(NODES-5)/5
      L=(LINK-5)/5
      A(L,N)=MAVS
      B(L,N)=MAVR
  104 CONTINUE
      CALL PLOT (10.,-11.,-3)
      CALL PLOT (0.,1.5,-3)
      CALL AXIS (0.,0.,15HNUMBER OF LINKS,-15,6.,0.,5.,5.)
      CALL AXIS (0.,0.,29HMEAN ORGANIZATION ITTERATIONS,29,8.,90.,
    A1,A2)
      CALL PLOT (0.,8.,3)
      CALL PLOT (6.,8.,2)
      CALL PLOT (6.,0.,2)
      DC 105 I=1,3
      NP=6-I
      A(6,I)=A1
      A(7,I)=A2
  105 CALL LINE (X(I),A(I,I),NP,1,1,I)
      CALL SYMBOL (.2,7.8,.14,3,0.,-1)
      CALL SYMBOL (999.,999.,.14,11H - 20 NODES,0.,11)
      CALL SYMBOL (.2,7.6,.14,2,0.,-1)
      CALL SYMBOL (999.,999.,.14,11H - 15 NODES,0.,11)
      CALL SYMBOL (.2,7.4,.14,1,0.,-1)
      CALL SYMBOL (999.,999.,.14,11H - 10 NODES,0.,11)
      CALL PLOT (10.,-11.,-3)
      CALL PLOT (0.,1.5,-3)
      CALL AXIS (0.,0.,15HNUMBER OF LINKS,-15,6.,0.,5.,5.)
```

```
      CALL AXIS (0.,0.,31HMEAN REORGANIZATION ITTERATIONS,31,8.,       PLD00520
     90.,B1,B12)                                                       PLD00530
      CALL PLOT (0.,8.,3)                                              PLD00540
      CALL PLOT (6.,8.,2)                                              PLD00550
      CALL PLOT (6.,0.,2)                                              PLD00560
      DC 106 I=1,3                                                     PLD00570
      NP=6-I                                                           PLD00580
      B(6,I)=B1                                                        PLD00590
      B(7,I)=B2                                                        PLD00600
  106 CALL LINE (X(I),B(I,I),NP,1,1,I)                                 PLD00610
      CALL SYMBOL (.2,7.8,.14,3,0.,-1)                                 PLD00620
      CALL SYMBOL (999.,999.,.14,11H - 20 NODES,C.,11)                 PLD00630
      CALL SYMBOL (.2,7.6,.14,2,0.,-1)                                 PLD00640
      CALL SYMBOL (999.,999.,.14,11H - 15 NODES,C.,11)                 PLD00650
      CALL SYMBOL (.2,7.4,.14,1,0.,-1)                                 PLD00660
      CALL SYMBOL (999.,999.,.14,11H - 10 NODES,C.,11)                 PLD00670
      GO TO 102                                                        PLD00680
  107 CALL PLOT (0.,0.,999)                                            PLD00690
      STOP                                                             PLD00700
C                                                                      PLD00710
  108 FORMAT (45X,A4)                                                  PLD00720
  109 FORMAT (10X,4I10)                                                PLD00730
  110 FORMAT (30X,2I10)                                                PLD00740
      END                                                              PLD00750
```

STANDARD TEST NETWORK

APPENDIX

Test Network Listed by Link Numbers

Link	Node-Node		Lgth.	Type	Link	Node-Node		Lgth.	Type
001	001	002	010	M	051	049	056	020	W
002	001	003	005	M	052	049	055	015	W
003	002	003	008	M	053	055	056	010	W
004	003	004	010	M	054	056	057	015	W
005	002	004	010	M	055	057	058	010	W
006	004	022	060	M	056	055	058	015	W
007	022	023	020	M	057	038	051	015	W
008	023	023	040	M	058	050	051	015	W
009	024	025	030	M	059	050	053	015	W
010	021	025	010	M	060	052	053	030	W
011	025	026	010	M	061	052	054	025	W
012	021	026	010	M	062	049	054	010	W
013	025	031	015	M	063	004	010	010	W
014	026	031	020	M	064	010	013	015	W
015	023	029	030	M	065	004	007	005	W
016	038	050	020	M	066	007	008	010	W
017	050	052	020	M	067	008	011	005	W
018	049	052	020	M	068	011	010	005	W
019	004	009	010	M	069	014	015	005	W
020	009	012	005	M	070	013	015	002	W
021	012	012	005	M	071	021	026	010	W
022	057	059	015	M	072	026	031	020	W
023	058	059	010	M	073	008	009	004	W
024	014	016	030	M	074	009	010	010	W
025	016	017	020	M	075	012	013	003	W
026	017	018	040	M	076	011	012	002	W
027	018	020	030	M	077	018	019	015	W
028	020	021	030	M	078	003	004	010	W
029	017	019	040	M	079	021	026	010	W
030	001	008	015	M	080	032	033	010	W
031	004	027	030	M	081	026	032	100	T
032	027	028	025	M	082	033	034	280	T
033	023	028	025	M	083	034	035	150	T
034	043	044	020	M	084	035	036	100	T
035	044	045	060	M	085	037	038	200	T
036	045	046	030	M	086	014	019	090	T
037	046	047	020	M	087	019	021	080	T
038	047	048	025	M	088	013	021	170	T
039	048	049	025	M	089	029	030	120	T
040	036	037	020	M	090	031	043	150	T
041	049	056	020	M	091	001	043	400	S
042	056	057	015	M	092	001	049	550	S
043	031	039	030	M	093	043	049	180	S
044	039	040	030	M	094	034	043	200	S
045	040	041	020	M	095	026	034	350	S
046	041	042	020	M	096	034	038	450	S
047	042	043	030	M	097	001	059	600	S
048	001	005	030	M	098	026	038	800	S
049	005	006	030	M	099	026	038	800	R
050	001	006	030	M	100	030	043	200	R

Test Network Listed by First Node Number

Link	Node-Node		Lgth.	Type	Link	Node-Node		Lgth.	Type
001	001	002	010	M	013	025	031	015	M
002	001	003	005	M	072	026	031	020	W
030	001	008	015	M	014	026	031	020	M
048	001	005	030	M	095	026	034	350	S
050	001	006	030	M	081	026	032	100	T
091	001	043	400	S	098	026	038	800	S
092	001	049	550	S	099	026	038	800	R
097	001	059	600	S	032	027	028	025	M
003	002	003	008	M	098	029	030	120	T
005	002	004	010	M	100	030	043	200	R
078	003	004	010	W	090	031	043	150	T
004	003	004	010	M	043	031	039	030	M
065	004	007	005	W	080	032	033	010	W
031	004	027	030	M	082	033	034	280	T
019	004	009	010	M	083	034	035	150	T
006	004	022	060	M	096	034	038	450	S
063	004	010	010	W	094	034	043	200	S
049	005	006	030	M	084	035	036	100	T
066	007	008	010	W	040	036	037	020	M
067	008	011	005	W	085	037	038	200	T
073	008	009	004	W	057	038	051	015	W
020	009	012	005	M	016	038	050	020	M
074	009	010	010	W	044	039	040	030	M
064	010	013	015	W	045	040	041	020	M
068	010	011	005	W	046	041	042	030	M
076	011	012	002	W	047	042	043	030	M
075	012	013	003	W	093	043	049	180	S
021	012	012	005	M	034	043	044	020	M
088	013	021	170	T	035	044	045	060	M
070	013	015	002	W	036	045	046	030	M
069	014	015	005	W	037	046	047	020	M
086	014	019	090	T	038	047	048	025	M
024	014	016	030	M	039	048	049	025	M
025	016	017	020	M	018	049	052	020	M
029	017	019	040	M	062	049	054	010	W
026	017	018	040	M	041	049	056	020	M
027	018	020	030	M	051	049	056	020	W
077	018	019	015	W	052	049	055	015	W
087	019	021	080	T	017	050	052	020	M
028	020	021	030	M	058	050	051	015	W
071	021	026	010	W	059	050	053	015	W
079	021	026	010	W	061	052	054	025	W
010	021	025	010	M	060	052	053	030	W
012	021	026	010	M	053	055	056	010	W
007	022	023	020	M	056	055	058	015	W
008	023	023	040	M	054	056	057	015	W
033	023	028	025	M	042	056	057	015	M
015	023	029	030	M	055	057	058	010	W
009	024	025	030	M	022	057	059	015	M
011	025	026	010	M	023	058	059	010	M

METRIC SYSTEM

BASE UNITS:

Quantity	Unit	SI Symbol	Formula
length	metre	m	...
mass	kilogram	kg	...
time	second	s	...
electric current	ampere	A	...
thermodynamic temperature	kelvin	K	...
amount of substance	mole	mol	...
luminous intensity	candela	cd	...

SUPPLEMENTARY UNITS:

Quantity	Unit	SI Symbol	Formula
plane angle	radian	rad	...
solid angle	steradian	sr	...

DERIVED UNITS:

Quantity	Unit	SI Symbol	Formula
Acceleration	metre per second squared	...	m/s
activity (of a radioactive source)	disintegration per second	...	(disintegration)/s
angular acceleration	radian per second squared	...	rad/s
angular velocity	radian per second	...	rad/s
area	square metre	...	m
density	kilogram per cubic metre	...	kg/m
electric capacitance	farad	F	A·s/V
electrical conductance	siemens	S	A/V
electric field strength	volt per metre	...	V/m
electric inductance	henry	H	V·s/A
electric potential difference	volt	V	W/A
electric resistance	ohm		V/A
electromotive force	volt	V	W/A
energy	joule	J	N·m
entropy	joule per kelvin	...	J/K
force	newton	N	kg·m/s
frequency	hertz	Hz	(cycle)/s
illuminance	lux	lx	lm/m
luminance	candela per square metre	...	cd/m
luminous flux	lumen	lm	cd·sr
magnetic field strength	ampere per metre	...	A/m
magnetic flux	weber	Wb	V·s
magnetic flux density	tesla	T	Wb/m
magnetomotive force	ampere	A	...
power	watt	W	J/s
pressure	pascal	Pa	N/m
quantity of electricity	coulomb	C	A·s
quantity of heat	joule	J	N·m
radiant intensity	watt per steradian	...	W/sr
specific heat	joule per kilogram-kelvin	...	J/kg·K
stress	pascal	Pa	N/m
thermal conductivity	watt per metre-kelvin	...	W/m·K
velocity	metre per second	...	m/s
viscosity, dynamic	pascal-second	...	Pa·s
viscosity, kinematic	square metre per second	...	m/s
voltage	volt	V	W/A
volume	cubic metre	...	m
wavenumber	reciprocal metre	...	(wave)/m
work	joule	J	N·m

SI PREFIXES:

Multiplication Factors	Prefix	SI Symbol
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
100 = 10^{2}	hecto*	h
10 = 10^{1}	deka*	da
0.1 = 10^{-1}	deci*	d
0.01 = 10^{-2}	centi*	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	µ
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a

* To be avoided where possible.

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